ARMY RESEARCH LABORATORY

Weapon System Implications of RLPG Technology

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Abstract

The primary purpose of this effort is to provide a preliminary assessment, from a weapon system perspective, of the applicability of LP gun (LPG) technology to the U.S. Army's anticipated future gun weapon systems needs, with particular emphasis on the Future Combat System (FCS), the intended replacement for the M1 main battle tank (MBT). The focus is at the weapon system level, as opposed to the details of implementation. Admittedly, these are often far from trivial, but they determine the difficulty of implementation and not the desirability of doing so. The secondary purpose is to provide, based on the current technology development status and as driven by the specific characteristics of the gun weapon systems discussed, the future development needs should the U.S. Army choose to continue development of this technology.

Acknowledgments

Forty years ago liquid propellant guns (LPGs) were little more than laboratory curiosities. The refinement of the regenerative liquid propellant gun (RLPG) technique and the development of the hydroxyl ammonium nitrate (HAN)-based propellants revolutionized this propulsion technology. As with the development of any technology, its evolution depended on the endeavors of a great many people, in industry, academe, and the government. This author was privileged to have worked with many of these people and is forever grateful for the professional and technically inspiring environment that their collective endeavors created. However, there were several individuals whose contributions were of such magnitude that they determined the development of this field. The development of the RLPG was led primarily by A. Graham, R. E. Mayer, and M. J. Bulman, at that time, all of the General Electric Company. Dr. N. Klein and Mr. C. Leveritt of the U.S. Army Ballistic Research Laboratory (BRL)* led the development of the HAN-based propellants. Lastly, little of this could have happened without the support of Dr. R. Eichelberger, then the director of BRL, and the programmatic and technical leadership of Dr. W. F. Morrison, also of BRL.

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* The U.S. Army Ballistic Research Laboratory was deactivated on 30 September 1992 and subsequently became part of the U.S. Army Research Laboratory on 1 October 1992.

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1. Introduction

1.1 Background and Purpose. The U.S. Army has made a significant investment in liquid propellant (LP) gun technology going back to the late seventies, the principal focus becoming the application of this technology to the next-generation self-propelled howitzer, the Crusader. The rate of progress of the maturation of this technology proved to be incompatible with the Crusader program schedule, and LP was replaced by a solid propellant (SP) modular charge. The U.S. Army is currently assessing its position with respect to LP as determined by its perceived future gun weapon system needs.

The primary purpose of this effort is to provide a preliminary assessment, from a weapon system perspective, of the applicability of LP gun (LPG) technology to the U.S. Army's anticipated future gun weapon systems needs, with particular emphasis on the Future Combat System (FCS), the intended replacement for the M1 main battle tank (MBT). The focus is at the weapon system level, as opposed to the details of implementation. Admittedly, these are often far from trivial, but they determine the difficulty of implementation and not the desirability of doing so. The secondary purpose is to provide, based on the current technology development status and as driven by the specific characteristics of the gun weapon systems discussed, the future development needs should the U.S. Army choose to continue development of this technology.

1.2 Organization. This report is organized in the following manner. Section 2 presents the author's approach to assessing the military worth of a concept or design. Section 3 presents a discussion of the manner in which the specific mission affects the utility of the concept or design. These discussions are presented to ensure that the reader has a clear understanding of the basis that the author has used to judge worth. The basis of Regenerative Liquid Propellant Gun (RLPG) technology rests on the LP and the hardware used to burn it in a controlled manner. Succinct discussions, sufficient to underpin system level considerations, of the propellant and the RLPG mechanism and hardware are presented in sections 4 and 5. A discussion of LP traveling charge (LPTC), an important derivative technology, is presented in section 6. A short discussion

of the artillery mission is presented in section 7. Section 8 focuses on the armor mission. The minor caliber and theater ballistic missile mission discussions are presented in sections 9 and 10. A summary and conclusions are presented in section 11.

2. Assessment of Military Worth

2.1 General Factors Affecting Military Worth. Assessing the military worth of a potential weapons technology must be done within the context of the military user's needs, as the one who procures and uses such equipment. These needs are easy to state, but translating them into the engineering language, which the development community must have in order to perform its function, is a complex and difficult process. In the first consideration, the user focuses neither on technology nor on subsystems based on that technology. The user interacts with a complete weapon system, of which a particular subsystem is only a part, although it may be the most important part.

From the user's perspective, the most important characteristic of the weapon system is that it be able to carry out its mission—that is the only reason for placing that weapon system and its crew on the battlefield. The next most important characteristic is that it, and particularly its crew, survive the mission. This is a very important element and is not driven solely by the survival instinct. From a military perspective, there must be enough left in the way of military power (i.e., forces, transportation, and supplies) to exploit the outcome of a battle. The third characteristic is the difficulty of living with the particular weapon system in the operational environment. This is measured in two ways, by the ease of use (what is referred to these days as the Soldier/Machine Interface) and by the effort required to keep it operational. The former is vital because it affects both training requirements and the speed of reaction during combat. The weapon system must be quick and simple to employ in its primary role. The latter determines both the logistical "tail" required to support that system and the training required at all echelons within the tail. It determines the availability of that weapon system for employment at any given time. If unit level (crew) required maintenance is high, this will also severely impact crew endurance and therefore performance over the course of an intense battle or long campaign.

These are the considerations that determine military worth as seen by the field forces, the real "users." But whether or not a particular weapon system is ever built is also determined by other factors, principally economic in nature. Bluntly stated, there is only so much money to go around, and so the weapon system must be affordable. This is usually couched within the language of "cost-effectiveness." Affordability consists of two elements, the initial acquisition cost and the life-cycle cost (LCC). Both must make sense within the context of the total spending pool available at any given time.

Another important aspect is what is required in the way of materiel to produce both the weapon system and its expendables. Can it be done within the constraints of the existing plant and equipment? Must new plants be built? How much and how long will this take? What about wartime surge requirements? There are also important factors that are not economic in nature, such as the need for scarce or critical raw materials. Is the availability sufficient to support the maximum foreseeable needs? Can supplies be interrupted by hostile forces?

But how are these important but imprecisely stated needs to be translated into terms that the development community can use to formulate the necessary research, development, and evaluation efforts? This is done by examining the functional requirements of the specific subsystem for which the technology in question is being considered, the ability to meet these requirements, the impact of the resulting subsystem on the total weapon system including the crew, the impact on the support system, and the impact on production requirements, i.e., plant and equipment and raw materials. Since this study is focused on a particular gun technology, the following discussion will be limited to the specifics that define these devices.

2.2 Factors Affecting Gun Technology. The most important element to keep in mind is that a "gun" does not have an independent existence in its own right. The obvious example is that guns do not destroy targets, which is the ultimate mission to be performed; rather, it is the munitions they launch that accomplish this. Thus, when one speaks of a "gun" within a military worth context, one must perforce include the ammunition as well. In fact, the constraint is stronger. Since it is the munition that accomplishes the actual task, the design of the gun is

primarily driven by the characteristics of the target kill mechanism and the munition design that has been selected to achieve it. In addition, for the missions of most interest, the allowable and necessary characteristics of the "gun" are also strongly constrained by being part of a complete weapon system platform. It is for this last reason that personal weapons such as rifles or pistols, or man-portable crew-served weapons such as machine guns, are not addressed in this document.

The fundamental requirements for launching the munition, although complex and interactive in nature, are easy to state. The gun must launch the munition at a desired velocity and in a given direction, within certain limits in terms of variation in both velocity and direction and without subjecting the munition to launch stresses sufficiently high to degrade its ability to destroy the target or too rapidly destroy the gun. With respect to the platform, the fundamental requirements are considerably more numerous, are also complex and interactive, and are more difficult to state concisely. They can perhaps most easily be appreciated by considering the platform, from a design perspective, as a series of budgets, for size, weight, cost, maintainability, supportability, etc. It is important to realize that these issues are of vital importance to the military user. System size and weight are critical to the user's ability to perform his mission. It affects his strategic and tactical mobility (ability to move the system to the theater of action and the ability to move around within that theater, respectively), his survivability (probability of detection, probability of hit, and probability of kill), and the tonnage that the logistical tail must provide on a continuing basis to support operation of that system. The current and foreseeable environment is such that reduced forces operating from the continental United States (CONUS) will be required to quickly and efficiently deal with a wide variety of overseas threats spanning a wide range of military capability. The overwhelming desire is to drastically reduce system size, weight, and cost, both acquisition cost and the cost of ownership. Unfortunately, the need to "efficiently" deal with the threat results in pressures that run counter to this desire. It is the difficult task of the development community to reconcile these conflicting requirements in a manner that results in optimal benefit to the user.

3. Emerging Mission Considerations

Technology development serves to either improve the user's current level of capability or to provide him with new capability. The user determines his needed capability by perceiving his role in satisfying the nation's future defense needs. This, in turn, is determined by the nature of the conflicts that are expected and the Army's resulting assessment of the DTLOMS (doctrine, training, leadership, organization, materiel, soldier) required to effectively fight such conflicts. The currently perceived future is characterized by a continuing pullback from forward basing, driven by the changing world situation, and an expectation that funding constraints will continue into the future.

The conflicts foreseeable for the next decade or two will take place in Second- or Third-World countries, but given existing proliferation of military technology, these countries are likely to have limited quantities of highly sophisticated and capable weapons. These conflicts will, in all likelihood, arise suddenly and require a quick and forceful response. It is also expected that the frequency of operations other than war (OOTW) will continue to increase. This is a very different environment from the one that the U.S. Army has trained and equipped for since World War II. Yet underlying all this is the continuing need to retain the capability to successfully fight a high-intensity conflict of the traditional type.

The U.S. Army Training and Doctrine Command (TRADOC) has concluded that the future DTLOMS of the U.S. Army must be such that it can respond quickly, violently, and overwhelmingly, exercising near total information dominance. Quick response requires high strategic mobility, which, in turn, requires small, lightweight systems requiring minimal logistics support. Violent response requires weapons with a high degree of overmatch against the enemy's defenses. These two factors are key to the design of weapons for the future ground battlefield. Continued funding constraints will dictate continued reductions in the Army's force structure. Given smaller forces, it will be necessary to use both control over battlefield information and a very high degree of tactical mobility to confuse, paralyze, and overwhelm the enemy. In summary, the Army believes that future conflicts will require it to transfer forces to

the theater of operation quickly, go over to the offensive immediately upon disembarkation, and maintain an exceedingly high operating tempo.

In general, for all future ground combat vehicles, these desired capabilities require that they be much smaller, much lighter, be much more easily supportable, require reduced crew, be far more survivable, far more mobile, incorporate much higher levels of electronic warfare, and be significantly more lethal. The technical challenges that these requirements represent are truly formidable.

The discussion thus far has focused on the traditional warfighting roles required for combating an opposing armed force. It is also recognized that we are entering an era where nontraditional roles, such as combating terrorism, have to be addressed. The nature of such attacks is extremely broad, ranging from the direct acts of a few individuals to threats posed by limited numbers of sophisticated delivery systems. This discussion will limit itself to threats that can be interdicted by gun systems, such as theater ballistic missiles (TBMs).

4. Propellant Characteristics

4.1 System Level Characteristics. The basic physics and chemistry that underlie the operation of both solid propellant guns (SPGs) and RLPGs are the same. This means that the requirements that determine selection of a desirable propellant are also the same and may be described as follows. The most important is mass energy density, particularly for high-velocity guns. High mass energy density minimizes the charge size required to achieve a given velocity. This has a very strong ripple effect throughout the weapon system and its supporting logistics system. First, it minimizes the size of the gun chamber, and therefore the gun size and weight. Second, it permits the storage of more charges in the vehicle, maximizing stowed load. At the same time, since both the mass of the charge and the breech are minimized, less power is required to support a given firing rate. These same considerations apply to the supporting logistics system. More charges can be stored at any given node, and it becomes easier to transfer charges between nodes.

The next most important characteristic is propellant sensitivity to initiation. This is crucial to weapon system survivability. It is often the storage of energetic materials within the platform that is the principal determining factor in survivability. For a given energetic material, achieving a specified survivability level drives not only weight, to prevent certain threats from penetrating to the propellant, but frequently internal configuration, to maximize crew survivability in case the propellant is initiated.

It is an unfortunate fact that energy density and propellant sensitivity represent opposing characteristics. In general, the higher the energy density becomes, the higher also the propellant sensitivity. Propellant sensitivity represents a severe constraint on which possible energetic materials can actually be used in weapon systems. This characteristic becomes even more important as the system weight, and hence the level of passive protection possible, is reduced.

Storage characteristics are also of vital concern to the user. He must build up large stocks of ammunition that will be immediately available to support a large-scale conflict. Years may pass before these are actually used. Once shipped to the theater of operations, it is desirable that they be able to withstand their environment without a significant level of assistance. Ambient temperatures can vary from well below freezing to desert conditions where metal surfaces can become too hot to touch. The importance, and the burden, of this issue can be readily seen from the manner in which SP charges are stored and shipped. The associated packing materials (i.e., metal cans, liners, wooden boxes) significantly increase the weight and volume that must be stored, shipped, and handled by the ammunition support system. They also create debris that can be difficult to deal with under field conditions.

The remaining most important generic factors are cost and strategic availability of the raw materials. Cost can be broken down into several factors: cost of the raw materials, cost of processing these raw materials into the final product, the cost of the plant required to perform this processing at the required capacities, and the environmental costs that this processing generates. In today's environment, this last item is a particularly sensitive issue. Strategic

availability requires that no enemy be able to cut off supply of any of the necessary ingredients in time of war.

4.2 LP Characteristics. No gun can be designed independently of the ammunition, the charge and projectile that it is to fire, and this linkage is particularly close for RLPGs. The required gun performance, specified by such factors as munition size, weight, and launch velocity, launch velocity reproducibility, and rate of fire, is the principal determinant in setting general gun characteristics such as size and weight. However, vital details, such as the choice of materials and the design of the ignition system, are driven by such propellant-specific characteristics as materials compatibility and ignitability.

From a systems perspective, the most important single characteristic of the LP is that it is a liquid. As such, it will not keep its own shape, and seals are always required to ensure that it does not leak from any container into which it is placed. Second, it can wet the surfaces that surround it, and contaminants can easily mix with it, so that materials compatibility becomes a critical issue. Third, it raises the issue of how propellant is to be transferred from point to point. SP charges are mechanically transferred as distinct elements. Suitably packaged, this is also a possibility for LP. However, unlike the case for SP, the LP may also be pumped, an important system consideration.

Generically speaking, any propellant consists of fuel-like components mixed with oxidizer-like components. Two types of LP systems are possible, monopropellant and bipropellant. In a bipropellant, the fuel and oxidizer components are stored as distinct entities and are only mixed when combustion is required. Depending on their nature, they may ignite spontaneously on contact (hypergolic) or may require a separate ignition stimulus (nonhypergolic). In a monopropellant, the two components are thoroughly premixed, down to the molecular level. Because a propellant is not formed until the two components are actually mixed, bipropellants can have a significant advantage in terms of high-energy density coupled with low sensitivity. However, this advantage comes at a cost in safety for tactical applications, which, at least until now, has been judged to be unacceptable. In a bipropellant, the fuel component is almost

invariably toxic (such as hydrazine) while the oxidizer component is extremely active chemically (such as inhibited red fuming nitric acid [IRFNA] at 95% concentration). It is impossible to design a totally leakproof system, and combat damage will cause propellant spills. Not even the best system design can prevent the crew from being exposed. The hazard to personnel has so far outweighed the benefits, particularly within the Army environment, with its distribution and resupply of propellant to a myriad of combat vehicles. Most monopropellants are also unsatisfactory from this standpoint. While they lack the extreme chemical activity, they are usually toxic.

4.3 Characteristics of the Hydroxyl Ammonium Nitrate (HAN)-Based Liquid Propellants. It is for these reasons that the development of the HAN-based monopropellants represents a remarkable breakthrough. The defining characteristic of these monopropellants is that the oxidizer is HAN, a crystalline solid that is almost 100% soluble in water. The fuel component is a complex amine nitrate, typically chosen to optimize propellant characteristics such as energy density, ignitability, or stability for a particular mission application. In LGP1846, the monopropellant chosen for the artillery application, the fuel component is triethanol ammonium nitrate. The final component is water. Besides serving to liquefy the active ingredients, the water content of the propellant is chosen based on the need to provide a reasonable energy density against the need for an acceptable level of propellant sensitivity.

The thermophysical properties of the HAN-based monopropellants have been extensively characterized.* Table 1 summarizes, from a systems perspective, the key properties of the 1846.

The following characteristics of these propellants need to be discussed in further detail: their utility for medium- and high-performance guns, their long-term storage stability, their storage efficiency, their resistance to detonation, their storage within the weapon system, and their associated costs.

* The literature is voluminous. For a typical summary, see Warren et al. [1]. This document is organized according to the propellant characteristics of interest, physical, chemical, and thermodynamic aspects, transportation issues, storage, health and safety, etc. Each section is extensively supported by a detailed bibliography.

Table 1. Propellant Characteristics

Good energy density, with impetus typically on the order of 900 J/gm.
Moderate flame temperature, on the order of 2500 K.
High specific heat, on the order of 2.3 J/gm-K.
High heat conductivity.
Electrical conductor.
No toxic vapors (vapor pressure due solely to water).
Low intrinsic toxicity
Moderately toxic for skin exposure, toxic if inhaled as an aerosol.
Adequate thermal stability.
Good storage stability when properly packaged.
Does not burn at low pressure, but does release toxic fumes.
Difficult to detonate.
No secondary flash or blast.
Can be made noncombustible by adding water or chlorine.

The XM46 was specifically formulated for the artillery role, and it is quite adequate for medium-velocity gun applications. However, these propellants are not good choices as propellants for high-velocity guns. Their mass energy density is simply too low. In simplified terms, the energy that is released by propellant combustion is converted into four areas, heating of the gun barrel, gas pressure, gas kinetic energy (KE), and projectile KE, which is the desired output. As the projectile velocity increases, and particularly once the sound speed of the gas is exceeded, more and more energy is locked up as KE in the gas at the expense of its pressure. This effect is axially highly asymmetric and produces the large disparity between the combustion pressure and the projectile base pressure that is observed in high-velocity guns. The gas KE is directly proportional to its mass (as measured by its mean molecular weight), and minimizing this pressure drop requires minimizing the mass of propellant that must be burnt to achieve a given level of energy release. Thus, for high-velocity guns, it is energy per unit propellant mass that becomes critical. This is why JA2, the propellant currently used for the M256 tank gun, has a mass energy density of 5075 J/gm as opposed to about 4035 J/gm for XM46, at a loading density of 0.2 gm/cm^3.

The long-term storage stability of these propellants, if stored in containers of the proper material, is at least as good as for SPs and in all probability is significantly better. Typical SPs are complex structures involving mixtures of several phases, some crystalline and some amorphous. Aging factors, such as temperature cycling, can degrade these propellants in a number of ways, among these being separation and migration of the various phases. This can change the ignition and combustion properties of these propellants to the point that they are no longer safe to use in gun systems. Their complex structure also limits the reproducibility of their properties. They are produced in large batches, and the properties of one batch are typically sufficiently different from another so that this difference must be explicitly tracked and accounted for in the ballistic solution. This adds a significant burden to their use. LPs, on the other hand, are simple mixtures that are homogeneous down to the molecular level, and it is quite likely that tracking of lot-to-lot variation may prove to be unnecessary.

The storage efficiency of these monopropellants, on the other hand, is greatly superior to anything that can be achieved with solids. This is for two reasons: (1) SP charges must be packaged as cylinders, and (2) sufficient porosity must be incorporated into the packaged charge to permit adequate flame spreading through the propellant bed during combustion. The combination of these two factors improves the storage efficiency of LP over SP by about 50%, or about 40% when converted to improved energy storage. The actual situation is actually somewhat more favorable to LP because of the reduced volume and weight associated with LP containers as opposed to the manner in which SP charges are packaged and shipped.

The behavior of these monopropellants when attacked by such concentrated energy sources as the high-speed jets produced by HEAT warheads is, from a systems perspective, one of their most interesting and potentially important characteristics. Testing has already demonstrated that they are insensitive to initiation by shrapnel. Initial testing with small HEAT warheads attacking quart-sized plastic containers filled with LP also yielded no initiation. These promising results were extended to larger quantities and more energetic warheads and produced mixed results. However, the details of the reactions induced were significantly different from those typical of SPs under similar conditions and appeared to indicate that the container played a significant role.

This still leaves open the important possibility that properly designed packaging could result in a high degree of insensitivity, a result which may be crucial as the Army continues to struggle to significantly reduce the weight of its future combat systems without sacrificing desired system requirements such as low vulnerability.

Storage of the propellant external and internal to the weapon system presents two different sets of issues. In external storage, the propellant is hermetically sealed (it is hygroscopic) and the only time that it can interact with materials other than its container is during the act of transfer. The container can then be recycled, suitably cleaned as necessary, and reused. This is not the case in internal storage. The internal storage tanks would, in all likelihood, be conformal to maximize use of interior volume, and removing them for cleaning would be difficult at best. There are also the lines, pumps, and valves that constitute the means for transferring propellant at a high rate into the gun. It will be impossible to completely avoid traps, thus propellant can sit in various nooks and crannies for long periods of time. A similar situation exists within the gun itself, which must contain flow passages, valves, and seals. Frequent usage will tend to reduce the concentration of any undesirable contaminants by diluting these pockets with fresh propellant. Still, the effect of such long-term, unintended exposure on both the propellant and the materials exposed to it needs to be determined. Periodic flushing with water is simply not practical. Quite aside from the fact that this will leave water in the lines, which would dilute the subsequent propellant charge, there is simply not the room to carry the necessary quantities of water. There is also the question of peacetime training. Ammunition is uploaded when the unit goes out to the field and is downloaded when it returns. What should the cleanup standing operating procedure (SOP) be? Do the tanks, lines, valves, pumps, and gun need to be flushed out?

The propellant raw ingredients are relatively cheap and are not strategically critical. Since there is no load, assemble, and pack (LAP), the finished propellant is also relatively cheap. Several production studies have estimated that, in quantity production and suitably capitalized, propellant costs would be about \$3/lb. The operation of a pilot production plant does not appear to contradict these estimates. This compares very favorably against SP charge costs, which can

be as high as $60–$100/lb. There are comparable savings in a plant and equipment. It has been estimated that building a new plant to produce stick propellant can run as high as $1 billion. In contrast, because production of the HAN-based propellants is basically a mixing process involving liquids, a plant with equivalent capacity can be built for $100–$150 million. A further and not insignificant benefit is reduced pollution. The residues and waste products from a HAN-based monopropellant production plant are markedly less than from any SP production plant. The U.S. Army is paying a high price today for environmental remediation. Also, unlike the case for SPs, it should be possible to monitor production quality sufficiently so that lot control, with its attendant need for extensive record keeping, should be unnecessary.

4.4 Future Trends. As stated earlier, the interaction between the propellant characteristics and the design of the gun is particularly strong for the RLPG. Improvements in propellant mass energy density, reductions in sensitivity, improved ignitability, and more complete combustion at lower pressures will have significant impact on the size, weight, safety, complexity, and therefore the cost of ownership of RLPGs. It is therefore important to note that promising research in HAN-based LPs is still ongoing [2]. Researchers at the U.S. Army Research Laboratory, Weapons Technology Division* (ARL-WTD) are now evaluating LGP 1915, which promises to have increased energy density (an impetus of 972 J/gm), improved ignitability, and improved thermal stability, and appears to burn to completion at relatively low pressures. Since it contains significantly less HAN than either XM46 or LGP 1845, its sensitivity may not be greater than for either of these two propellants. Furthermore, stabilizer additives, developed to negate the effect of transition metal contaminants in XM46, appear to perform equally well in this new class of propellants [3].

The important point to remember is that this is still an immature technology with considerable scope for further improvement of the product.

* The Weapons Technology Division is now the Weapons and Materials Research Directorate.

5. Regenerative Gun Technology Description

5.1 Comparison of LP and SP. Detailed descriptions of the regenerative process for controlling the combustion of LPs in guns have been provided by numerous authors [4, 5]. This author will limit the description of this process to only those essentials required to give clarity and weight to the system considerations, which are the primary concern of this report.

The first key point is that the basic mechanism involved in the propulsion process is the expansion of a hot, high-pressure gas. Thus, from a propulsion perspective, the basic considerations are no different than for any such device (e.g., SPGs and light gas guns). The distinguishing characteristic of all LPGs is that the gas is produced by the combustion of an energetic liquid. All evidence indicates that the physical mechanism underlying this combustion is the idea that the surface area exposed to heat is, as is the case for SPs, the fundamental mechanism at the heart of the gas generation process, although the details of this mechanism differ significantly from those present in the combustion of SPs. The total gas generation rate can be viewed in the same terms as for an SPG. It is the product of the total surface area and the gas generation rate per unit surface area. The latter is driven by the chemistry of the propellant and, stated in terms of surface regression rate, is typically on the order of 1 cm/s, as it is for SPs. Given the power generation actually observed in guns, the required surface regression rate is several orders of magnitude higher. This increase must be provided by increased surface area. Furthermore, if the gun is to meet its requirements on velocity reproducibility, there must also be tight control on the magnitude and evolution of this surface area. In the SPG, this is accomplished through granulation of the propellant. This is clearly not an approach that can be used with a liquid.

5.2 RLPG Fundamentals. In a regenerative gun, surface area production and control is done by generating a huge number of small droplets, a number so large that shot-to-shot statistical variations in those factors that control the combustion of any given drop (principally size and velocity) become inconsequential. This is accomplished by forcing the liquid through specially contoured orifices at very high differential pressures, typically 10,000 psi. But this,

however, raises another problem, namely, how to achieve such a differential pressure in an energy, volume, and space efficient manner against the very high back pressure present inside the gun during combustion. For artillery guns, this back pressure is typically 50,000 psi, while for tank guns, it can be as high as 100,000 psi. A number of studies have been performed examining the feasibility of pumping the liquid into the combustion chamber of the gun during the combustion cycle. The power required is enormous. It can be estimated from the expression $Q\Delta P$, where Q is the volume flow rate and ΔP is the differential pressure. For a 155-mm artillery gun, operating at relatively high zone, a typical propellant charge volume is 10 liters (about 2.5 gal), injected in 5 ms with a pressure gradient of about 10,000 psi. This corresponds to a power of about 174,000 hp. From a size and weight standpoint, providing this level of power externally is simply not practical.

In the RLPG, the approach adopted is to tap the combustion process for the necessary power by incorporating a differential area piston as illustrated in Figure 1, with the piston shaft protruding into the atmosphere. The propellant charge is injected into the gun prior to firing and positioned between the back face of the piston and the front of the breech. Provided that atmospheric pressure is negligible compared to the pressure in the combustion chamber, and under steady-state conditions, the pressure in the propellant reservoir will exceed the pressure in the combustion chamber by the ratio of the piston front face area to the piston back face area. This excess provides the pressure differential required to drive the propellant into the combustion chamber during the combustion process.

For the propellant to flow from the reservoir to the combustion chamber, these two volumes must be connected by suitable orifices. These orifices must be sized and contoured to ensure that the peak performance, related to total orifice area, is safely achieved. The flow of the liquid monopropellant through these orifices is at high speed, typically on the order of 10,000 in/s, and it is essential that the flow be controlled so as not to ignite the propellant prematurely. From an energy standpoint, this mechanism is surprisingly efficient, requiring only about 0.1% of the energy released during combustion.

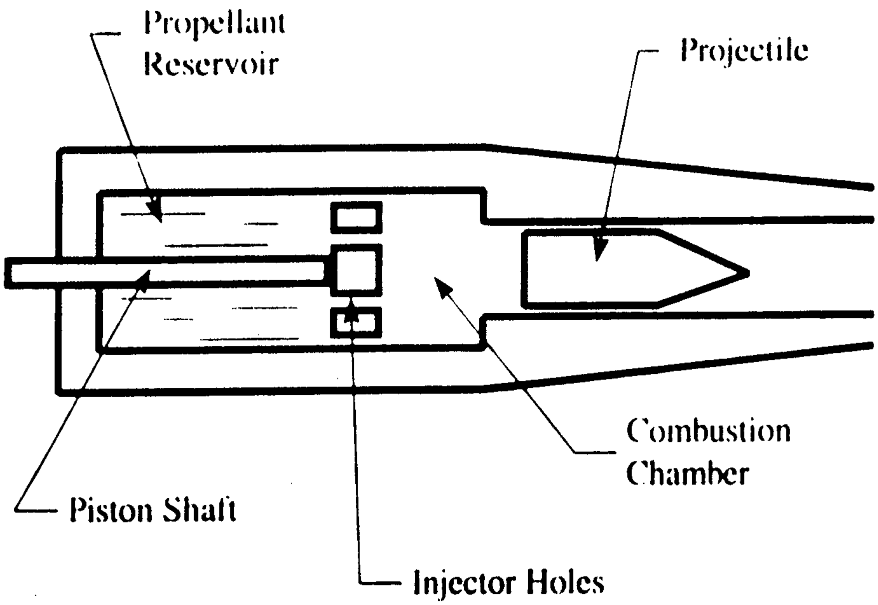


Figure 1. Schematic of RLPG.

For this process to work, it requires the pump to be "primed." This is done by providing an auxiliary ignition system, which generates enough hot gas to raise the initial combustion pressure to some predetermined value. This is equivalent to the bayonet igniter in a tank gun round, or the combination of the primer and base pad in an artillery charge.

Implementing a design in such a "self-contained" manner is highly efficient from a size and weight standpoint, but it also creates some inescapable system drivers. These drivers are consequences of the detailed nature of the regenerative process. The following discussion illustrates some key examples.

An important aspect of any gun is its response time. Once the gun is given the signal to fire, its response must be very quick, typically no more than a few tens of milliseconds. The equivalent question in a regenerative gun is the response of the injection piston to the pressure produced by the igniter. At gun pressures, liquids are quite compressible. The physical mechanism underlying injection piston response is that of a simple spring/mass system, with the piston acting as the mass and the propellant acting as the spring. The response time is given by the natural frequency, which can be approximated as

$$\nu = (1/2\pi)\sqrt{BA/ML},$$

where B is the propellant compressibility, A is the piston face wetted area, M is the piston mass, and L is the length of the propellant reservoir. It is very important that ν be large, as it is highly desirable that the propellant reservoir pressure follow the rise in combustion chamber pressure without significant under- and over-shoots. Examination of the previous expression shows that this requires large values for B and A and small values for M and L. From a system perspective, the driver for a regenerative gun is for a short, wide gun chamber rather than a long, narrow one. Although this does tend to reduce overall gun length, the net result is an increase in gun weight, because weight increases linearly with increasing chamber length and as the square with increasing radius.

From the standpoint of achieving performance, reducing response time, and ensuring that any induced pressure oscillations do not cause difficulty with reversed flow of propellant through the injection orifices, RLPGs are typically designed with differential area ratios of 1.2 to 1.5. However, this raises the propellant reservoir pressure significantly, and the increased pressure must be compensated by increased thickness of the outer gun chamber wall. This increased wall thickness again drives the system to increased weight.

5.3 RLPG System Considerations. The number of ways in which these two principal functional requirements can be physically implemented appears to be very large. Numerous physical configurations have been conceived, analyzed, and a significant number have actually been built and tested. Two of the more prominent and most explored configurations, referred to as VIC and reverse annular piston (RAP), respectively, are illustrated in Figures 2 and 3. In VIC, the injection piston consists of a two-piece structure. The outer piece (referred to as the injection piston) is hollow, and its shaft rides along the inner surface of the gun chamber wall. It is in the shape of an annulus. Its size is determined by the relative position of the elements making up the total piston. A retarding force, typically implemented as a variable hydraulic damper, is applied to the shaft of the control piston and is used to control the velocity of this

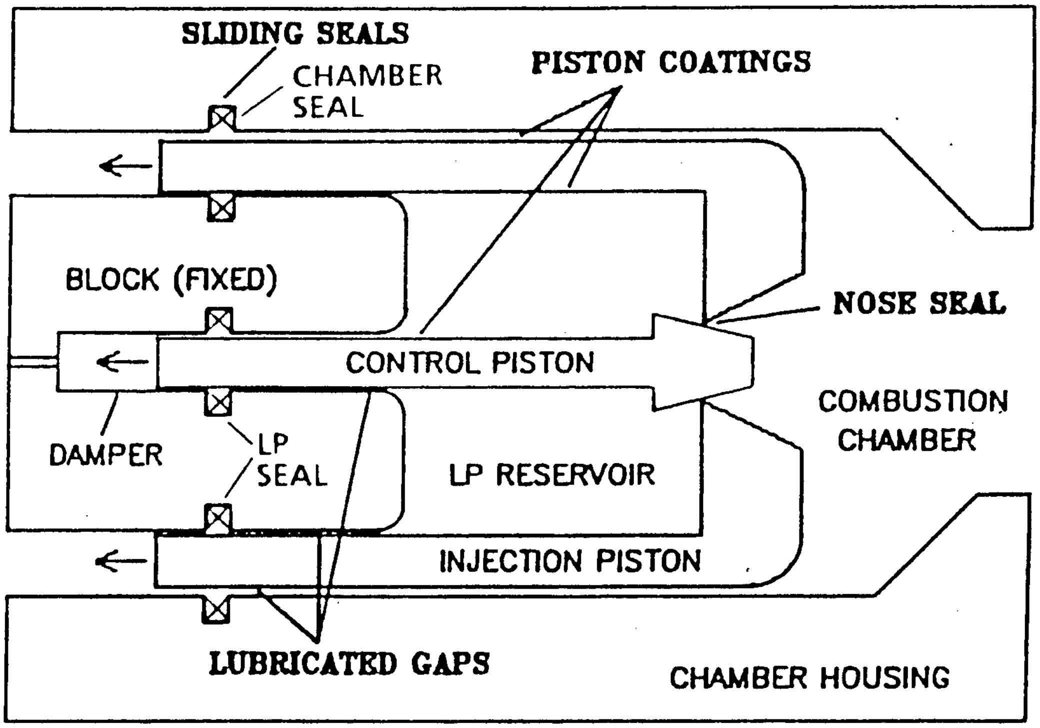


Figure 2. Schematic of Concept VIC.

Reverse Annular Piston (RAP) Ballistic Cycle

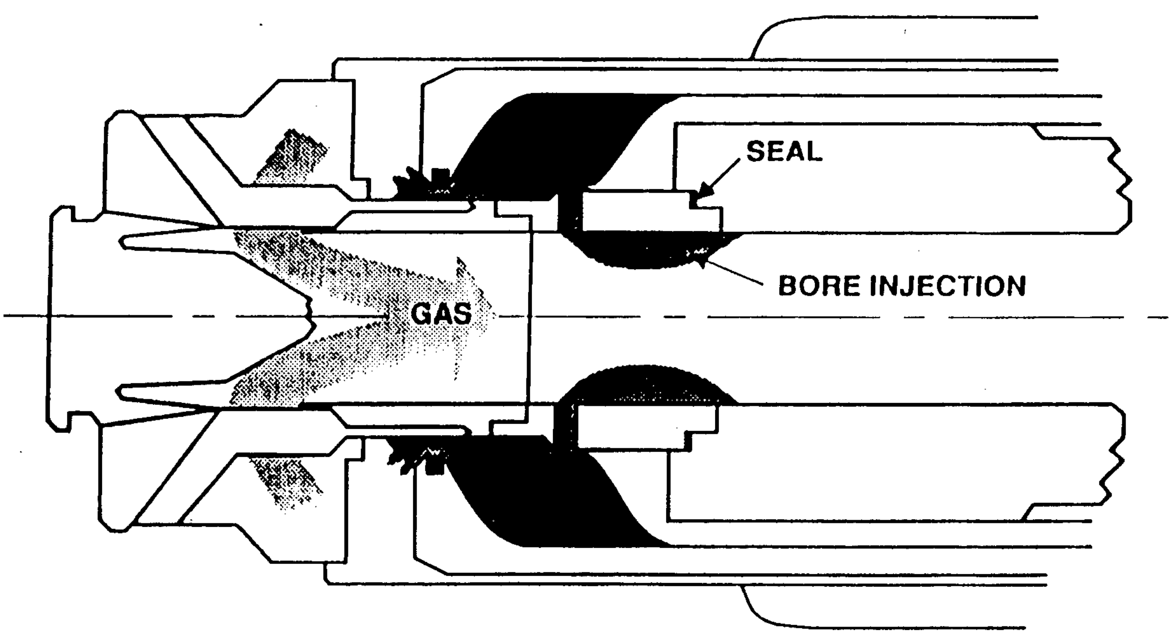


Figure 3. Schematic of the RAP.

element during firing. During firing, the separation between the two pistons is determined by the velocity of the control piston. Since the peak pressure, and hence gun performance, is determined by the rate of propellant inflow into the combustion chamber, damper control of the inner element provides direct control over gun performance. This provides a flexibility that is not possible with an SPG, where the equivalent characteristic, propellant granulation, is fixed during manufacture. This is a characteristic that could become very valuable if the future battlefield demands significantly higher launch system flexibility.

In the RAP, the injection piston is also hollow and is now wrapped around the gun barrel with the piston shaft again riding against the inner wall of the gun chamber. Propellant injection typically occurs in two locations, directly into the region in front of the piston face and also directly into the gun bore. Control of propellant injection area is severely limited as compared to VIC.

A comparison of these two configurations will illustrate the main differences, which, from a systems perspective, distinguish the myriad of possible configurations. The key is the overall physical arrangement of the major elements. In VIC, the regenerative mechanism and its housing are directly in line with the gun bore, while in the RAP, it is wrapped around the gun bore. For the same projectile travel, VIC results in an inherently longer gun than does the RAP. However, the gun chamber is narrower for VIC than for the RAP. From a systems perspective, the most crucial difference is the impact on projectile loading. VIC requires translation of the entire regenerative mechanism and its housing, while the RAP can use a conventional breech. VIC therefore requires both significantly more free space to allow the translation of such a large body and significantly more system power to accomplish such a translation, power which is also driven by the need to satisfy high firing rates. Quite aside from the design complexity, which this introduces into VIC, the power requirements are not negligible. The exact value of the power required depends on the precise nature of the technique used to separate the breech from the barrel. The 155-mm version of VIC, designed for a firing rate of seven rounds/minute, required a peak power of about 90 hp and an average power of about 10 hp to operate the breech. Estimates for achieving 12 rounds/minute range from an average power of about 30 hp to peak

powers as high as 180 hp [6]. Providing this power level within the confines of a combat vehicle represents a significant drain on the space and weight budget of the vehicle.

To properly assess the system impact of RLPG technology, a comparison with SP technology is in order. First, for equivalent propellant mass energy density, and for the same level of gun performance, an RLPG will always exceed an SP gun in size and weight. For the sake of argument, let us assume that LPs and SPs exist that have the same mass energy density. For purposes of this comparison, we will use the simple configuration shown in Figure 1. A highly simplified analysis, one which assumes that the SP and LP have equivalent mass and energy densities (an assumption that is very favorable to LP) and high gun performance (which requires a high regenerative ratio), results in a conclusion that, for equivalent gun performance, the chamber volume of an RLPG is on the order of 50% greater than that for an SP. This will also result in a comparable increase in gun weight. A more careful analysis of this question may be found in Warren et al. [1] and reaches similar conclusions.

One key hidden assumption in this analysis is that the conversion efficiency, the ability of the device to convert chemical energy into projectile KE, is equivalent for both the RLPG and the SP. At least for the RAP configuration, which is the configuration of choice for high-performance applications, this assumption has been experimentally verified in 30-mm firings.*

In gross terms, the following comparison between RLPGs and SPGs can be made. Both have equivalent ability to achieve performance, at least as compared to today's systems (velocities on the order of 1.7–1.8 km/s). For equivalent performance, the gun chamber of an RLPG will be larger and heavier than for an SPG. The RLPG requires internal moving parts that must operate in a very hot, high-pressure environment, while the SPG does not. The RLPG can vary its performance level with far more precision and control than an SPG. For the 155-mm artillery application, the inherent ballistic reproducibility of an RLPG has been demonstrated to be superior to that of an SPG.

* This was done by General Electric Ordnance Systems (GEOS) using in-house funding in the early eighties.

A somewhat different but very illustrative perspective on the difference between the two is as follows. An SPG can be regarded as a simple cylinder with a reusable closure at one end. Virtually all the complexity is in the fabrication of the propelling charge, which is manufactured at the plant. Once manufactured, the characteristics of this charge can no longer be changed. The commander has the responsibility of determining the mix of charge types that will be required for a given mission, and the logistical system must stock and supply the appropriate variety and quantity. The RLPG, on the other hand, can be regarded as a propellant plant in the field. The LP serves as an undifferentiated raw material, and the gun makes up the charge as required for the mission at hand, and this is why it is significantly more complex mechanically than its SPG counterpart.

6. The Traveling Charge

6.1 Process Description. The traveling charge is a technique for altering the physics governing the interior ballistics to achieve a significantly higher level of ballistic efficiency than is possible for the conventional interior ballistics cycle. In a conventional interior ballistics cycle, all the propellant is burned at the breech end of the gun. As the projectile accelerates and moves away from the combustion chamber, the energy required to accelerate the gases to the base of the projectile comes at the expense of the local pressure. The projectile base pressure is therefore less than the combustion chamber pressure, and this effect becomes more and more pronounced as the projectile velocity increases, roughly as the square of the velocity.* More and more of the propellant energy is devoted to merely accelerating the combustion gases to the base of the projectile and less and less to accelerating the projectile itself. For high-velocity guns, this results in a rapidly increasing charge-to-mass ratio. The gun chamber must be proportionately larger to accommodate this charge, fewer charges can be stored, and the increased vehicle volume devoted to propellant storage can result in a significant increase in system vulnerability.

* This simplified analogy makes use of the Bernoulli equation, which states, within broad assumptions, that the total energy density at any point in the flow, measured as the sum of the kinetic and potential energy densities, remains unchanged. Since the KE density is proportional to the square of the flow velocity and the potential energy density is proportional to the gas pressure, the local pressure must drop by a factor of four whenever the local flow velocity doubles.

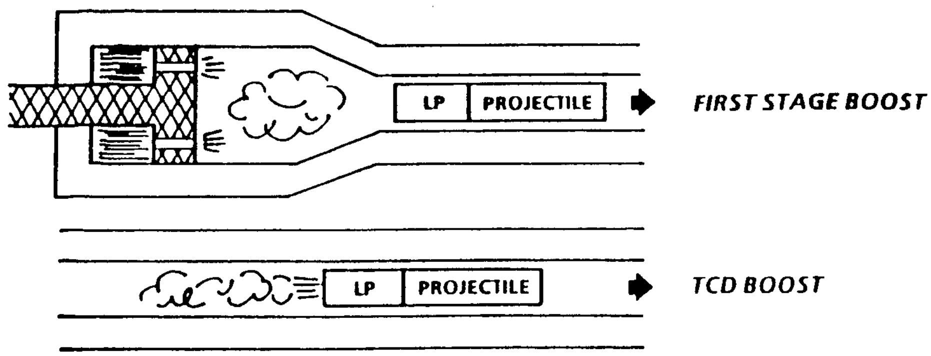
The impact on the logistics system supporting this platform is similar. The increased gun chamber size, together with an increase in the operating pressure in an attempt to improve conversion efficiency, also results in a significant increase in gun weight.

The traveling charge technique is an attempt to mitigate this penalty by burning an appropriate quantity of propellant in the immediate proximity of the projectile base. In the classic traveling charge (TC), since the gases are created already moving at the projectile velocity and in the immediate vicinity of the projectile base, there is little further pressure drop. A schematic of the TC concept is shown in Figure 4. In broad outlines, the TC technique operates as follows. Part of the propellant charge, typically on the order of one-half, is attached by some means to the projectile so that it is initially accelerated with it. The remainder of the propellant charge is burned in the gun breech to generate the pressure required to accelerate the combination of the projectile and the remaining charge. Conventional guns are exceptionally efficient at converting chemical energy to KE at velocities below sound speed. The charge split is therefore typically chosen so that the breech charge is powerful enough to accelerate the combination of propellant and projectile to approximately 1 km/s (typical sound speed). At this point, the charge attached to the projectile is ignited and the projectile acts as an in-bore rocket, with the gun barrel walls serving as the rocket motor casing. The projectile becomes at this point a surf rider, riding on the pressure wave that is generated at its base and moves with it.

Theoretical studies have indicated that the pressure structure created is highly unstable. In particular, theoretical analysis done by Dr. Paul Gough indicates that once combustion ceases, it quickly readjusts to a Lagrangian type of distribution, with the difference being that, compared to a conventional interior ballistics cycle, there is less total energy in the gas as the projectile KE is now higher. Thus the system design point is to achieve burnout within two calibers of travel of the muzzle [7].

The TC interior ballistics cycle was first proposed by the Germans during World War II [8, 9]. Its theoretical basis has been studied by numerous investigators and is well understood. Numerous attempts to implement this mechanism using SPs have all ended in failure. The

The Liquid Propellant Traveling Charge (TC) Concept



- ***Initially launched by a solid or liquid propellant (first stage)***
- ***Acts as a high pressure, in-bore rocket (second stage)***
- ***Avoids drop in ballistic efficiency associated with conventional expanding gas ballistic cycle***

Figure 4. LPTC Schematic.

stumbling block always centered around the need to achieve propellant linear regression rates that were typically three orders of magnitude than what was typical of SPs.

6.2 General Electric Armament Systems (GEAS) Test Results. Over the last several decades, the attempts to implement TC behavior have been lead by ARL at Aberdeen Proving Ground, Aberdeen, MD. The litmus test chosen to indicate achievement of TC behavior was that the measured projectile velocity exceed the predicted velocity for a conventional interior ballistics cycle operating at the same charge mass, projectile weight, projectile travel, and peak pressure by at least 10%. In the early 1980s, GEAS internally funded a program to investigate several implementations of the TC mechanism using LPs rather than SPs.* The test fixture used was a 30-mm RAP configuration LPG operating at a peak chamber pressure of about 50 ksi. For the implementation referred to as fractional traveling charge (FTC), their experimental results are summarized in Figure 5. The vertical axis represents the charge-to-mass ratio, and the horizontal

* This work was performed at GEAS, Burlington, VT, as part of its internally funded Internal Research and Development (IR&D) program. The work was performed in a period ranging from the late seventies to the early eighties. During this time, another implementation of LPTC, referred to as the traveling charge dispenser (TCD), was also investigated under contract to ARL.

VELOCITY VS. CHARGE TO MASS RATIO FOR 1.52 M OF PROJECTILE TRAVEL

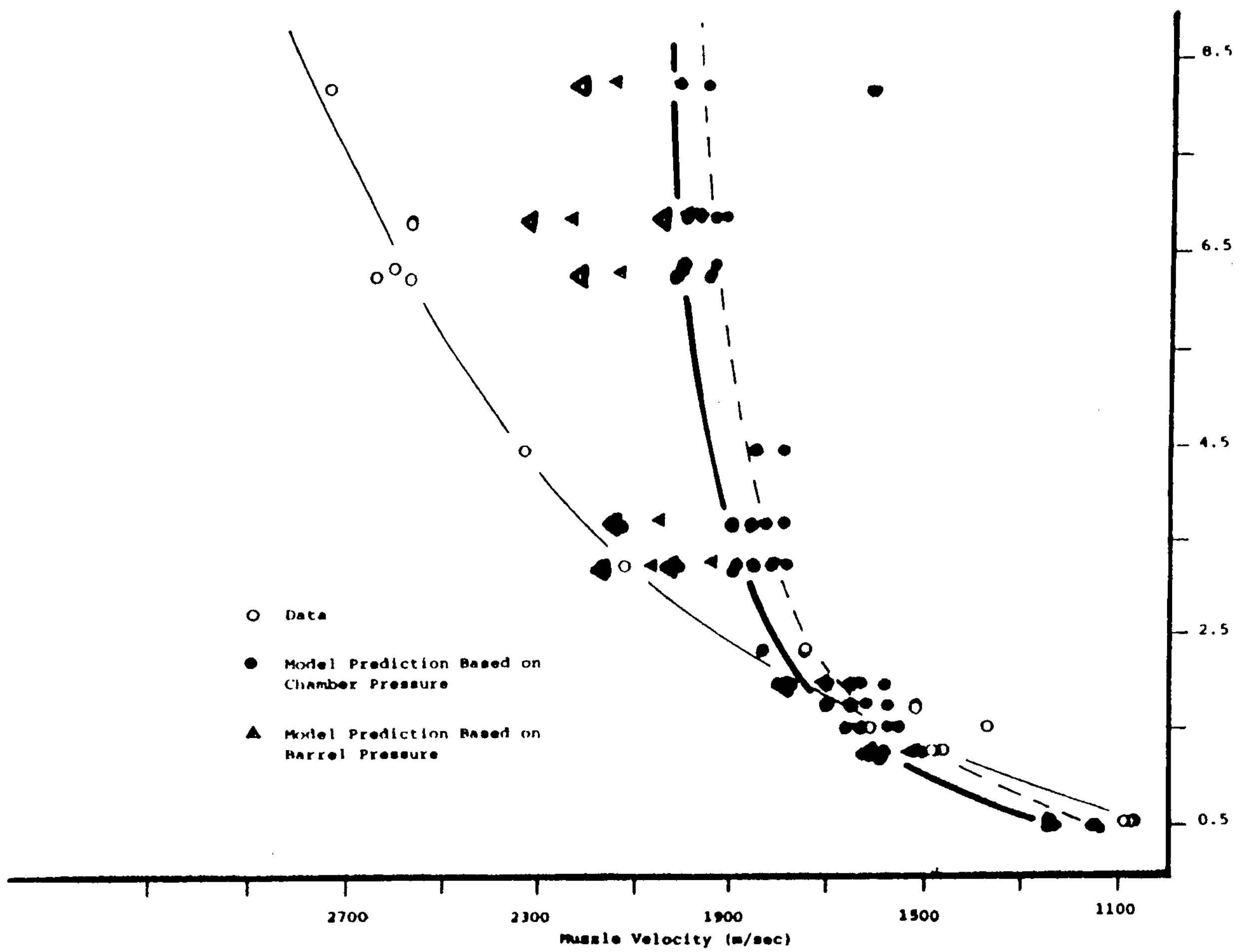


Figure 5. Comparison of 30-mm LPTC Test Results Against Equivalent SP.

axis the muzzle velocity. The open circles represent the measured data, and the filled circles the predicted performance of a conventional cycle SPG operating at the same propellant and projectile mass, the same peak pressure, and the same projectile travel. Predicted performance was obtained using the Mayer-Hart formalism [9]. The experiment also incorporated a number of down-bore pressure gauges. Where a measured down-bore pressure was higher than the chamber pressure, this pressure was used as the input to the Mayer-Hart formalism to generate the SPG performance prediction. These results are indicated by triangles. It is also assumed that the LP and SP have the same impetus. Solid gun propellants represent a much more highly

developed field than do liquid gun propellants, and the SPs used in tank guns have a significantly higher impetus than do LPs. To assess the impact of this disparity, the solid line represents the predicted performance assuming JA2 propellant energy density.

It can be seen from these data that, once the charge-to-mass ratio exceeds 2, the interior ballistics cycle employed by the test fixture resulted in significantly superior conversion efficiency. The improvement observed cannot be explained by improper pressure measurements nor can it be equaled by the best existing SP tank gun propellants. The projectile design was also such that these results can also not be explained as measurements of the fastest moving fragments of a broken projectile. Below the cross-over point of two, the conventional interior ballistics cycle outperforms the interior ballistics cycle operating in this test fixture, a result expected from TC theory.* Based on these results, together with a careful examination of the measured pressures, the investigators at GEAS concluded that TC behavior had been observed.

These results, while very significant, should not be overstated. Although feasibility was demonstrated, engineering practicality remains to be established. Performance and repeatability both depend critically on precise control of the time of ignition of the charge traveling with the projectile. Within the context of this series of experiments, the time of initiation of this secondary charge proved very difficult to control. Significant pressure fluctuations were also measured down-bore. Subsequent examination of the gun barrel showed measurable distortion of the gun bore surface. On the other hand, these results were obtained for combustion pressures in the range of 50–55 ksi. Increasing the operating pressure to 75–100 ksi should significantly improve conversion efficiency, for both the conventional and TC interior ballistics cycles. It of course needs to be demonstrated that the mechanisms underlying LPTC operation will still perform satisfactorily at these significantly higher pressures. Furthermore, acceptable behavior in small caliber is not a guarantee that equivalent behavior can also be achieved in larger caliber. Thus considerable work remains to be done before this technique can be applied in practice, and

* Since some of the charge is initially accelerated with the projectile, this represents a case with an extra heavy projectile, which would underperform the equivalent charge in the breech accelerating only the projectile itself.

the severity of the problems remaining to be encountered is not known. It is, however, this author's opinion that, from a weapons systems perspective, such a pursuit has many advantages.

6.3 Weapon System Consequences. The weapon system consequences of LPTC can be most easily presented in the following manner, using the results shown in Figure 5, even though the operating pressures used in these test firings were unrealistically low. Higher pressures, on the order of 75 ksi, as a gross estimate would reduce the charge-to-mass ratios on the order of 30–40%. However, from a system perspective, they would still remain uncomfortably large and would not qualitatively change the following arguments.

Let us first suppose that the remaining technical issues can be successfully resolved and that this technique can be successfully reduced to practice. Suppose, for the purpose of this argument, that it was desired to develop a gun that operated at a charge-to-mass ratio of 5.5. Then, using the conventional interior ballistics cycle, a gun could be designed that would have a certain weight, volume, projectile travel, and charge size and would launch the projectile at about 2 km/s. However, if the design of this gun were based on the TC interior ballistics cycle, this same gun, having the same weight and volume, employing the same charge size and firing the same projectile, could launch that projectile at about 2.5 km/s. It is this author's opinion that, for velocities significantly above the conventional cycle/TC cycle cross-over point, the TC cycle represents the minimum volume, weight, and charge size configuration required to launch a projectile to a given velocity of any known propulsion means, including electromagnetic (EM) launch and such exploratory technologies as reliability, availability, and maintainability (RAM) projectiles. It therefore presents the smallest penalty in terms of integration into a platform with a limited space and weight budget. This is characteristic of all of today's Army ground combat vehicles and will be even more so in the future. It still remains to be determined, of course, that such velocities will be truly beneficial on tomorrow's battlefield.

This is, of course, a zero order argument. There are detailed differences that will have at least some impact on size, weight, and complexity. Higher down-bore pressures will require a heavier barrel, resulting in a heavier gun and with a larger unbalance requiring more powerful

elevation drives. Achieving a higher launch velocity in the same distance of travel requires a higher acceleration, with more stress on the projectile structure, and therefore probably a more robust projectile. There is also the question of the intrinsic size and weight of an RLPG compared to an SPG of equivalent performance. Earlier discussion indicated that the weight disparity can be on the order of 50%, not an insignificant weight penalty. However, there is no theoretical reason why such a gun cannot be designed as a hybrid, using an LPTC and an SP breech charge.* Such a configuration, however, would lose the system integration benefits associated with employing liquids. Properly introducing the LP into the gun barrel during the loading process is also not a trivial design issue.†

A much more important issue is the systems implication of the charge-to-mass ratio, which is very severe. A charge-to-mass ratio of 5.5 means that the projectile charge weighs 5.5 times the projectile mass. In the current 120-mm tank gun, which launches a 7.12-kg projectile at about 5500 ft/s, the charge-to-mass ratio is about 1.1, or about 7.8 kg of propellant. If the projectile mass were to remain unchanged, a charge-to-mass ratio of 5.5 would require 39.2 kg of propellant. The gun chamber would have to be five times larger, with the attendant increase in size and weight and, if the vehicle weight and volume were to remain unchanged, the stowed load would be reduced by significantly more than a factor of five. The impact on the logistical system would be equivalent. This does not even take into account such gun-peculiar factors as an enormously increased barrel wear, requiring such frequent rebarreling as to be unacceptable under combat conditions.

Operating the system at a higher pressure, say on the order of 100 ksi, would significantly reduce the magnitude of the charge-to-mass ratio required to operate at this velocity. It would not, however, materially alter either the logic or the conclusions of the previous argument.

* Some preliminary work on such a hybrid system has already been performed at ARL using a 40-mm test fixture with Mr. I. Stobie as the principal investigator. The results were not entirely satisfactory, but the goals set may have been too extreme for the existing state of process understanding.

† A preliminary concept study integrating an LPTC into a 120-mm tank gun was performed by Aerojet under contract to GEOS [5].

This situation is not unique to the TC interior ballistics cycle. It is true for all propulsion cycles. For guns, it is also true of EM and electrothermal chemical (ETC) propulsion. The most that can be said for the TC interior ballistics cycle is that it represents the least growth in system size and weight (and probably complexity) for a given percentage increase in velocity, once the velocity significantly exceeds the crossover value. What this analysis also says is that, from a weapons system perspective, hypervelocity (velocities on the order of 2.5 km/s), no matter the specific launch technology employed, will only be useful if the kill mechanism involved permits a significant reduction in projectile launch mass.

Exploration of the potential gun consequences of LPTC has been limited. Some theoretical ballistic calculations have been attempted, however. A typical example is shown in Figure 6.*

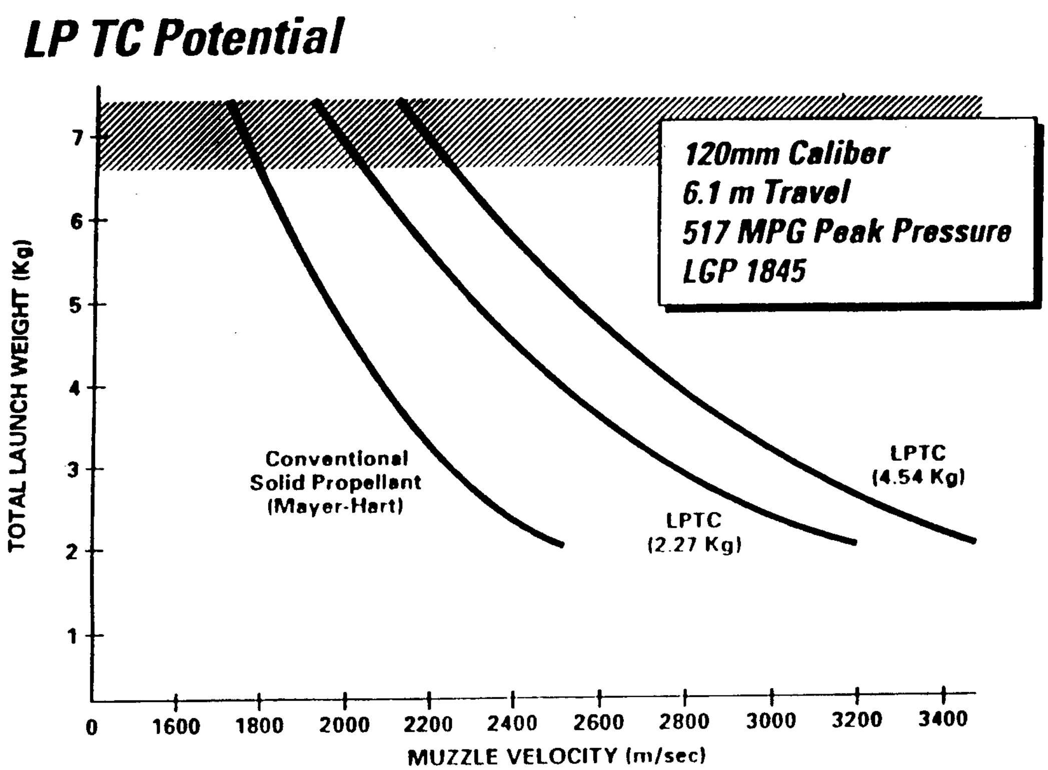


Figure 6. Sample Ballistic Calculations of LPTC Potential.

* These calculations were performed by GEOS in the early eighties as part of an in-house funded effort to investigate application of LP to high-velocity guns. A simplified theoretical approach, linearly adding a rocket-type model for the TC to a Mayer-Hart analysis of gun performance, was employed.

There are also many nontrivial implementation issues associated with integrating LPTC into a gun, either RLPG or SP. However, given the current state of the art, further pursuit of this area should be according to the following logical path: the establishment of hypervelocity utility against targets of interest followed by a demonstration of control and scalability of the LPTC mechanism.

7. The Artillery Application

7.1 Key System Benefits and Burdens. The Artillery Mission has been the beneficiary of the bulk of the regenerative liquid propellant technology development efforts, and the system benefits, burdens, and remaining technology development needs are therefore well established. The key system benefits are:

- the ability to fire each type of round to its maximum range capability (because of the infinitely variable charge capability of LP and the ability to maintain a flat pressure/time trace in the combustion chamber).*

- the potential to provide time-on-target (TOT) fire across most of the range capability far in excess of what SP can provide (see Figure 7).

- on the order of a 50% increase in stowed load.

- significantly lower LCC because of lower cost of raw materials and elimination of LAP costs.

- tighter velocity reproducibility.†

* The RLPG can be designed to achieve a pressure just below the projectile permissible individual maximum pressure (PIMP) and hold this pressure until all the propellant is burned, an ability that an SPG cannot match.

† In limited testing of Gun 2 at Yuma Proving Ground, a top zone (999.5 m/s) repeatability of less than 0.2% 1 σ against a requirement of 0.25%. Testing at the lowest zone produced a 1 σ variation of 0.88% against a target of 1% [10].

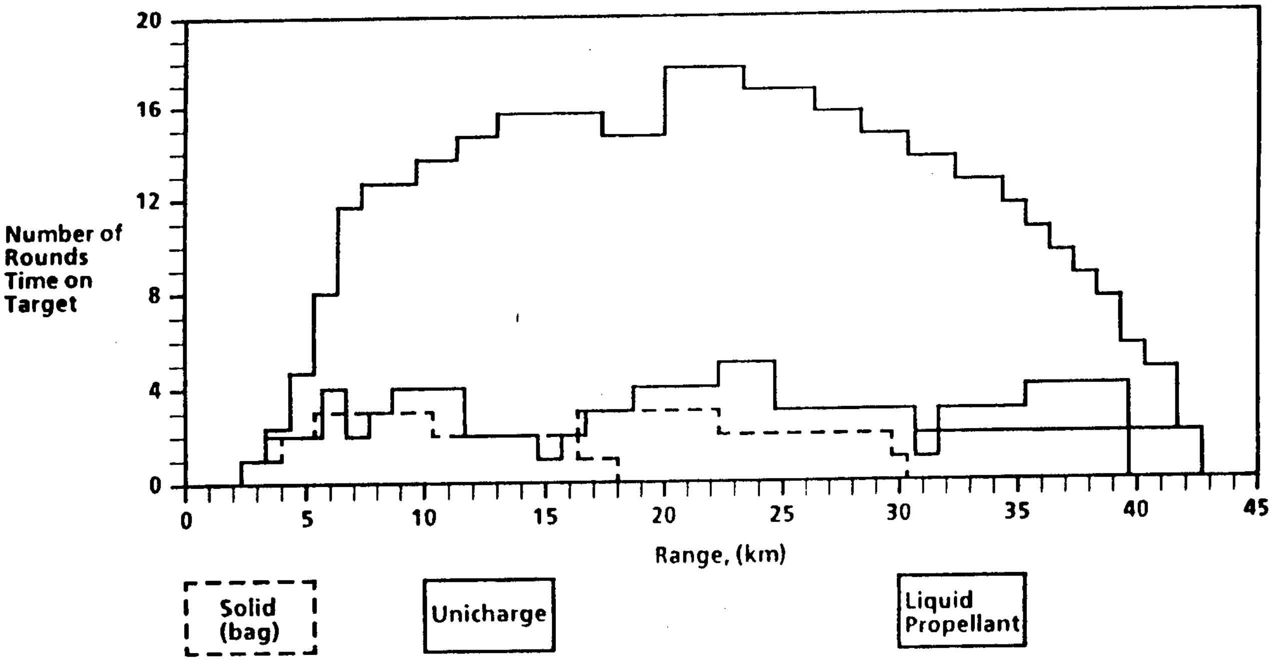


Figure 7. Comparison of SP, Unicharge, and LP TOT Performance.

- reduced muzzle flash and blast, important particularly at the highest zones.

The key system burdens are:

- significantly higher complexity, which could result in higher maintenance and spares stockage requirements.

- the swept volume, weight, and system power burdens associated with having to move the entire combustion chamber in order to insert the projectile, characteristic of the in-line RLPG concepts, such as VIC.

- additional consumables, such as grease and oils.

It is important to note that, although the key system burdens can be alleviated through optimal design (and perhaps selection of a different RLPG configuration), they can never be entirely eliminated.

7.2 Further Development Needs. For this mission, RLPG technology is fairly well developed. The key remaining development needs lie in the area of the artillery gun hardware.

7.2.1 The LP. For this mission, the level of development of the propellant XM46 appears to be adequate, or reasonably close to being so. Several production approaches have been identified and explored, and one, the electrochemical approach, has been taken through the pilot plant stage. The ingredients are available, and the plants required for support of both peacetime and wartime needs appear to be affordable. The physical properties have been extensively characterized, and the toxicity and hazard characteristics have been exhaustively studied and found to be acceptable. The Surgeon General has issued a preliminary approval for this material.

7.2.2 Propellant/Gun System Interaction. The situation with respect to interaction of the propellant with the gun system is considerably more complex but appears to be reasonably under control, with clearly identified pathways to achieve acceptable behavior for most of the known issues. The first question is storage stability, and a great deal of successful effort has been devoted to this question. When sufficiently free of metal contaminants and enclosed by compatible materials, such as passivated glass or selected flourine-based plastics, XM46 has outstanding storage stability, even at elevated temperatures. Chemical additive packages have recently been developed, which allow use of relatively common stainless steels as container materials [11].

Another key issue, critical from the system perspective, is detonability. XM46 is not easy to detonate, and in quart-sized quantities, in appropriate containers, has been demonstrated to be very resistant to detonation. Tests at the 50-gal level, crucial for practical storage and handling of this material, have shown mixed results, depending on the orientation of the incoming jet from the HEAT warhead. Analysis of test results indicates that the initiation mechanism is different from that of SPs, with bubble formation at wall boundaries playing a key role. These results indicate that it may be possible to design containers that significantly reduce the possibility of detonation, well below that expected for SPs of equivalent energy density and quantity.

Considerable effort has already been devoted to storage container design. In addition to addressing materials compatibility and detonability, this was done to evaluate the system-level benefits for the ammunition support system. All such studies have concluded that there would be significantly improved efficiencies in storage, handling, and transportation. However, little attention has been paid to transferring propellant from these containers into the using vehicle. Two general methods are possible, direct pumping, as is done in refueling a car, and transfer by complete container, as is done for milk cartons in a cafeteria. The issue in question is how to keep the propellant from becoming contaminated during the transfer. This is important because such transfer must occur under all environmental conditions. The ground environment can become quite dirty and invasive, as exemplified by operations in wet, muddy terrain or desert dust storms. The complete carton approach is clearly superior in this respect, but its impact on weapon system design (providing large enough access passages, moving large and quite heavy objects, etc.) is so severe that it is probably impractical. There is the additional problem of on occasion having to move these containers by hand. Direct pumping is clearly the preferred approach, and it should be possible to design a self-cleaning nozzle that fits into a receptacle which, once locked in place, hermetically seals this interface.

Of more concern is storage of propellant inside the using vehicle. The Propellant Storage and Handling System (PSHS) consists of tanks, pumps, lines, and valves. Furthermore, the choice of configuration, routing, materials of construction, and operational usage is severely constrained by the overall combat vehicle system design constraints. There are many detailed considerations, but they can be grouped into five categories: materials of construction, need for and difficulty of completely emptying propellant, propellant interaction with pumps and valves, the effect of dead pockets on contaminant concentration, and the impact of leaks. There is also the issue of energy management in the flow during dynamic operation. Flow rates can be very high. It is important to ensure in the hydrodynamic design of the propellant fill system that the flow passages are such as to minimize the possibility of cavitation and recompression, in all the elements that make up the flow path.

The issue of materials of construction has been referenced earlier. Acceptable choices are available and, as mentioned earlier, significant progress has been made in developing additive packages to dramatically improve propellant storage stability.

In peacetime, ammunition is uploaded when a unit goes out into the field for training and downloaded when the unit returns to the barracks. In wartime, the flow of ammunition is typically one way, being used up by the firing vehicle. The issue specific to LP is that it is almost impossible to completely drain any hydraulic system. There will always be some dead spots, pockets that can only be flushed out by using a fluid that dissolves the propellant, and there will always be some drops clinging to all the wetted interior surfaces unless the system is blown dry. What will be the impact of this as the equipment sits in storage for weeks and maybe even months? Will slow corrosion of the exposed surfaces occur? Will the level of contaminants in the dead zones build up to the point that autoignition occurs as the system undergoes normal temperature cycling? These questions need to be addressed. It should be pointed out that there is probably a fairly straightforward remedy for this. In peacetime, water is readily available. After propellant download, the system can be flushed with water and blown dry with air. Simply leaving it exposed to the environment should dry it out completely in a matter of days. During wartime, this should not be an issue. Frequent flow of propellant throughout the system due to gun firing, complemented by frequent resupply with fresh propellant, should thoroughly mix all the propellant in the system and prevent any local buildup of contaminant concentration.

Propellant pumps are another important issue. Pumps for two operating modes are required. The first is for transfer of propellant between containers and from containers to the using vehicle. Typical flow rates are 50–100 GPM, and these pumps can be large bore and low pressure, on the order of 100 psi. The effectiveness of such pumps has already been demonstrated.*

Pumping propellant from the PSHS to the gun is a more demanding and more complex issue. If the gun itself is to meter the quantity of propellant that it accepts, then a continuous or

* This work was performed by both GEAS and Aerojet.

semicontinuous pump design, such as centrifugal or peristaltic, can be used. However, because of limitations of line sizes going into the gun, these must be high pressure, on the order of 500 psi or higher. Care must then be taken to ensure that the pump design is such that it will not cause the propellant to ignite prematurely. If the metering must be done externally to the gun, and if the precision is to be very high, less than 0.1%, then metering cylinders must be used as the final step. This is the design used in the recent XM300 program.* It is important to note that, from a system safety standpoint, pumps may be preferable to metering cylinders. The latter are strong, closed-volume devices, while the former are not. In principle, considerably less damage might occur if propellant ignition occurred inside a pump, then inside a metering cylinder.

The specific issue with valves depends on their location, in the fill system, or in the gun. In the fill system, they must be designed so that there are no entrapped air pockets, the flow of propellant through the valve does not result in local cavitation, and the valve is self-draining under gravity. Inside the gun they must be rugged enough to withstand the very high-pressure environment and, above all, seal well enough so that combustion gases do not blow back through them and ignite the neat propellant. Depending on the firing rate and duration, special steps may be required to prevent them from overheating and igniting the neat propellant through heat feedback. This is a critical safety issue, and the steps taken to address it thus far, purging this region with either dry nitrogen or water between firings, simply are not practical. Its criticality will require a layered, redundant approach, possibly incorporating a series of valves, to ensure that a single point failure does not lead to a premature ignition. This is a key issue, which has not received the attention it requires.

All hydraulic systems are subject to leakage, and it is important to determine how much effort needs to be invested in preventing such leaks. The hydraulic system on board any combat vehicle is subject to some flexure and usually a high degree of vibration, which can eventually lead to both loosening of hydraulic fittings and fatigue failure of components such as lines. If the leaked propellant remains unpressurized, the worst case is that the propellant will undergo the "fizz" mode of decomposition. Depending on the quantity of propellant involved, this may

* XM300 is the designation for the 155-mm RLPG prototype.

require evacuation of the vehicle, but is not necessarily particularly dangerous. However, as the "fizz" decomposition is exothermic, if it occurs in the presence of combustibles, a fire could result. In a combat vehicle, anything that is small or loose eventually winds up in the bottom of the vehicle. An interesting experiment would be to take a vehicle just in from the field and pour a small quantity of propellant down the hatch.

There is one scenario where leaks would almost certainly be highly dangerous, and that is a pinhole leak in a pressurized propellant line. This would cause the interior volume to almost immediately fill up with a propellant mist. In addition to being toxic, given the vastly increased surface-to-volume ratio, this would probably be explosive, even given the difficulty of igniting the HAN-based propellants at atmospheric pressures.

In general, system safety from an unwanted propellant ignition standpoint has not yet been adequately addressed on a systematic basis. This is admittedly not a simple issue as it depends critically on the specific details of the design of the hardware controlling propellant storage and flow. Much has now been learned about the capabilities and characteristics needed in a PSHS and its counterpart internal to the gun, together with potential sources of unwanted ignition. A new, highly simplified design needs to be done, particularly for the PSHS. This design should be carefully analyzed for potential ignition sources and the design modified to eliminate these. The design must be such that if such an ignition should occur, it should not lead to catastrophic failure. It should be quite possible to do this. The natures of the potential consequences are well understood, and a number of incidents have clearly shown that, for the HAN-based propellants, combustion ceases as soon as the pressure is relieved.

Propellant ignition is another key unresolved issue. From a system perspective, it is undesirable to employ an expendable that is not already present to implement the ignition function. It is for this reason that so much emphasis has been placed on electrical initiation. The design was based on the use of a high-voltage spark to ignite a small quantity of propellant, roughly 1 cc, which was then amplified in two successive stages to generate sufficient thermal energy to reliably ignite the in-flowing propellant. The details of the extensive attempts to

develop a reliable ignition system on this basis may be found in the literature [12–14]. These efforts, at best, achieved only limited success. Although the design of the initial stage was reasonably successful, the later stages constantly suffered from combustion anomalies. Furthermore, it is possible that this basic design may have been unacceptably sensitive to gun elevation. This is one of the more difficult of the remaining development issues and still needs to be addressed.

*7.2.3 **Gun Development Issues.*** Perhaps the best known issue associated with RLPGs is the presence of large amplitude, high-frequency pressure oscillations [15, 16]. It should first be noted that these are not an inherent feature of the regenerative process. The showerhead configuration (see Figure 1), even in the 105-mm caliber,* was relatively free of these oscillations, as were the firings of the 30-mm RAP configuration, which reached pressures on the order of 90 ksi in the combustion chamber. With one exception, these oscillations were extremely prevalent in all the configurations employing annular injection, even in 25 mm. The exception occurred for annular injection configurations, which employed an extremely shallow taper on the center bolt, a result that was very consistent but has never been understood.

The mechanism that gives rise to these oscillations is still not fully understood. It clearly involves the combustion chamber geometry, the injection orifice configuration, the igniter geometry, the propellant characteristics, and the operating pressure. Measured in terms of either gun damage or erratic performance, there do not appear to be any obvious gun consequences for the presence of these oscillations in small-caliber gun fixtures. The situation is quite different for large-caliber gun fixtures. Here it is clearly associated with deformation and metal erosion, particularly on the nose of the central control piston. It also appears to be responsible for the loosening of parts, as all gun fittings had to be tightened after only a few firings of the 155-mm test fixture. But the central concern has been their impact on the projectile. Modern artillery projectiles are frequently buses that carry small, relatively fragile submunitions. If the natural frequency of any projectile component is similar to that of the pressure oscillations, vibration

* Eleven tests in a showerhead configuration in a 105-mm caliber using OTTO Fuel II were performed by the GEOS in the late seventies. Chamber pressures did not exceed 25 ksi. The bandwidth of the recording system was about 100 kHz.

amplitudes can build up to destructive levels. A few test firings were carried out with instrumented projectiles, but the results, although generally positive, cannot be said to have been conclusive.*

On the other hand, significant progress was being made in controlling this phenomenon [17]. This progress was made through trial and error by concentrating on such issues as proper damping and lubrication of the injection piston. Indeed, by program termination, the team had reached the initial goal set for reduction in these oscillations, at least for moderate charges.† Thus it appears that, although the mechanisms underlying this phenomenon are not well understood, promising approaches to their control had been identified.

The last important issue that still needs to be addressed is lubrication. Indeed, the RLPG being developed for the artillery application was frequently referred to as "the grease gun" because of the large quantities of lubricant it consumed per shot. The lubricant was used primarily around the injection piston, to lubricate its motion and to damp its oscillations. This lubricant is an expendable, and the logistical system not only needs to deliver projectiles and propellant but lubricant as well. This lubricant also needs to be stored in the vehicle and requires its own pumping system to insert it into the appropriate locations in the gun after each firing. Ideally, the use of this material should be eliminated. Since this will probably not be possible, the design must be such that the quantity required per shot be greatly reduced from current requirements.

7.3 Towed Artillery. Because of its importance to the warfighter, the focus of application of novel propulsion techniques to artillery has been the self-propelled howitzer (SPH). However, important elements of the Army are also equipped with towed artillery. Virtually no analysis has yet been devoted to the question of applying RLPG technology (or any other novel propulsion technology, for that matter) to this application. A very cursory examination was performed by

* It has been reported that YPG personnel described a recovered telemetry package to be in better shape than similar packages recovered from SP firings.

† The most successful modification employed was a "flow splitter." However, it remains unclear if this modification can be implemented within the context of a practical overall configuration [6].

GEOS, with the important conclusions being that zoning would no longer be continuous but rather would be implemented by means of mechanical stops and that sufficient propellant could be stored in the trails and pumped into the gun by hand.

The attraction of pursuing this question further lies in simplifying the logistic system by having only one type of propellant. However, in this author's opinion, detailed analysis of this question is unlikely to yield an attractive result. The essential characteristics of towed artillery lie in its small size and weight and, above all, in its simplicity. Converting towed artillery to the use of LPs would significantly complicate their design. Furthermore, liquids are simply a much more natural fit to designs based on powered hydraulics rather than on muscle power and fit SPHs far more naturally than towed artillery. It appears unlikely that the benefits of such a change would outweigh the burdens.

8. The Armor Mission

8.1 Role of Armor. The mission of armor is to overwhelm the enemy through a combination of shock, firepower, and mobility. This mission is central to winning today's conflicts and is still central to TRADOC's vision for winning future conflicts. The current embodiment of this mission is the Abrams series of MBTs, one of the most effective weapons on today's battlefield. It has excellent cross-country mobility, good range and endurance, outstanding armor, and mounts the most powerful gun in existence today. It also weighs 70 tons, combat loaded, and its main gun is marginal to ineffective against the new armor systems currently in development. To retain the armor mission within TRADOC's vision of future conflicts, it is necessary to at least maintain all current capability, improve lethality, and drastically reduce required logistics support, all within a weight limitation of 15–20 tons. This is clearly no mean feat and is the reason why, for the first time since prior to WWII, the Army is looking at design of the FCS (the successor to the Abrams) as a clean sheet of paper.

TRADOC's vision of the future Army, as expressed in the Army After Next (AAN), will not be in effect until about the year 2020. The two decades between now and then will see a mixed

force, one in which AAN-driven systems will gradually predominate. However, the M1 series of MBTs will be a mainstay of U.S. armor for many years to come. Upgrades of this system will be periodically required to ensure that it maintains its overmatch against the threats it is likely to face.

8.2 Force XXI Upgrades. Force XXI is the terminology that the U.S. Army has adopted to describe the mixed force (current systems plus AAN systems) that will be in existence for the next several decades. The first question is therefore whether or not retrofitting an LP main gun into the M1 can significantly improve its combat power. This is relevant because the Abrams will form the backbone of the armored force for several decades, and there will continue to be a need to improve it to meet the evolving threats. Several system studies have been performed to address this question, all reaching the same qualitative conclusions. The most recent and most comprehensive was performed by GE Aerospace and GM Military Vehicles Operation in 1982 [18]. The following summarizes the scope of the study, its principal study constraints, and the major findings.

The purpose of the study was to compare and contrast, at the systems level, the impact of new SP and liquid main armament on a future MBT, but one whose system architecture followed the lines of the current Abrams. The gun caliber was chosen to be 140 mm, firing suitably designed KE and high-explosive antitank (HEAT) ammunition, and the performance level for both rounds of both the SP and LP cannons was to be identical. The study encompassed selection and conceptual design of the LP cannon and propellant storage and handling system, their integration into a representative conceptual MBT, an operational assessment of the resulting weapon system, an LP armament technology development plan, and a preliminary acquisition plan. System performance requirements were those specified by the Future Armored Combat System (FACS) program, and the overall design of the MBT was taken from the studies that supported FACS. The requirements, which were principally responsible for driving the results of this study, were a three-man crew, a minimum stowed load of 44 rounds (two-thirds KE and one-third HEAT), a high rate of fire for KE (8–12 rounds/minute), and a high level (classified) of survivability.

The principal results were as follows. Although the LP main armament was about 50% heavier than the SP armament, the LP armed vehicle was about 3 tons lighter than the SP armed vehicle. Furthermore, the SP armed vehicle never met the required KE firing rate and its survivability was inferior to that of the LP armed vehicle. This initially surprising result is, however, quite understandable. It was driven by the gun performance, firing rate, and system vulnerability requirements. The performance requirement dictated the use of a 140-mm gun, the ammunition for which was so large that two-piece ammunition had to be used. To achieve the firing rate, the ready rounds had to be in the turret bustle, already assembled. The propellant charges are the most vulnerable components in the vehicle and are the prime determinants of system K-kill. Achieving the required vulnerability meant that the bustle had to be heavily armored, which added significantly to weight. In the LP armed system, only the projectiles were stored in the bustle, the propellant being pumped from tanks low in the vehicle. The bustle could therefore be much more lightly armored and still achieve the required protection level.

These results are thus due to the requirements imposed, but these requirements are typical of the capability that the user is seeking, at least for the time period of Force XXI. They can therefore be taken as representative of the impact that could be expected by incorporating LP into an MBT, provided that the basic architecture of the vehicle (turreted, with at least two men in the turret) does not change.

8.3 Remaining Development Needs. The remaining development needs are discussed in the following sections.

8.3.1 Propellant Development. Unlike the case for the artillery mission, there is a need to improve the mass energy density of the propellant. The mass impetus of JA2, the SP used in the current M256, is about 1200 J/gm, while that of XM46 is about 900 J/gm. This is a very large penalty to overcome. To meet given launch requirements requires the use of significantly more propellant, requiring a larger and therefore heavier gun chamber, reducing stowed load, increasing vulnerability (over what it would otherwise be for LP, still probably lower than for SP), and reducing barrel life. The development of LGP 1915 by ARL is an encouraging sign that there may be room for significant improvement in this category.

8.3.2 ***Propellant/Hardware Interaction.*** With one exception, the considerations with respect to propellant interaction with the hardware (gun and PSHS) are largely the same as discussed in the section on the artillery mission. The exception is vulnerability. MBTs expect to be attacked by the most powerful weapons present on the battlefield. The use of heavy armor, with all that this entails in the way of reduced strategic and tactical mobility and increased logistics support, is there to provide the necessary minimum level of survivability. This issue is so important that any opportunity to improve it should always be carefully considered. Converting the main gun to LP does represent such an opportunity. As discussed earlier, the LP itself, properly packaged, may be significantly less vulnerable than SP. Not only is the presented area of LP smaller than an equivalent energy of SP, but it can be stored away from the aim point, thus further improving survivability. There is also the ability of separately storing the fuel and oxidizer components within the vehicle. Although both HAN and triethanol ammonium nitrate (TEAN) are low-energy monopropellants in their own right, they are dramatically less detonable than the fully mixed propellant.*

The fuel and oxidizer would be mixed in the ratios necessary to form the propellant as it entered the gun. The ability to do so has already been demonstrated, albeit in smaller scale, in investigations studying the application of HAN-based monopropellants as torpedo propellants.† Propellant flow rates were on the order or 20 gm/s, with combustion in the chamber occurring at about 1400 psi. In all cases, combustion was smooth and reproducible. The machinery required for accurate mixing is neither bulky nor complex. However, there is a system cost, with the PSHS becoming almost twice as complex. The impact on the logistics system would also be undesirable, requiring handling and coordination of two individual components, neither of which is of any use without the other. There is also the question of ensuring that the physical and chemical properties of the two components are such that they would be compatible with both the logistics and vehicle environments. However, given the potential reduction in K-kill, this possibility deserves careful consideration.

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* HAN and TEAN have been investigated as components of a binary explosive round. As part of this effort, the detonability of each component was investigated and found to be negligible [11].

† This work was performed by Lockheed Martin Defense Systems under contract to the Naval Underwater Weapons Center in the early nineties.

This approach would probably require that the tanks holding the two components be heated, as their phase diagrams indicate a relatively high freezing point. This, however, should not be particularly difficult or cumbersome to implement.

8.3.3 Gun Design Issues. There are also a number of issues related to the design of the LPG. First, the logical choice of RLPG configuration is the RAP, because of its small swept volume for inserting the projectile. This is particularly advantageous in a turret mounting, because of the extreme emphasis placed on minimizing volume under armor. For an RLPG, the space required is further reduced because, unlike the case with an SPG, only the projectile and not the entire round has to be lined up axially with the bore for gun insertion. Because the propellant can be pumped, an RLPG also avoids the problem of having to deal with two-piece ammunition, the solution adopted for SPGs of caliber larger than 120 mm.

Some work has already been done evaluating the RAP for this role. An experimental investigation was carried out by GEOS using IR&D funding in a 30-mm RAP configuration geometrically scaled to the 120-mm tank gun.* These investigations used LGP 1845 as the propellant. In order to account for the lower impetus, the projectile travel was increased proportionately. Using a 110-gm projectile with a peak chamber pressure of about 75 ksi, velocities of about 1700 m/s were routinely achieved. The basic conclusion was that, regarded as a device for converting chemical energy to KE, the RAP is at least as efficient as an SPG operating within the same thermodynamic limits.

From a system perspective, there also exists one key, nontrivial design requirement for the RAP to permit it to be the main armament of an MBT. The tank gun must be able to fire not only KE rounds, but HEAT as well. For the current M256, the HEAT to KE projectile mass ratio is about 2, and it is fired at a significantly lower velocity than the KE round (about 1 km/s vs. 1.65 km/s). This implies at minimum that the internal gun propellant flow rate must be adjustable, or else either required KE launch velocity will not be achieved or an overpressure

* This work was performed by GE Defense Systems as part of an internally funded investigation as to the feasibility and desirability of applying LP technology to high-velocity applications.

will occur when the HEAT round is fired. Some design studies have been performed to address this problem, but none of the approaches considered have yet been tested in hardware. From an implementation standpoint, the most intriguing approach is shown in Figure 8. Here the short barrel is allowed to float, with the clearance between the short barrel and the main barrel forming an annular injection area into the gun bore. The thickness of this annulus, and therefore the propellant flow rate for a given pressure gradient across this annulus, is determined by a hydraulically controlled mechanism incorporated into the breech. Clearly, the basic idea has considerable flexibility, as it should be possible to position the short barrel continuously between a maximum and a minimum gap, including zero gap for propellant fill. This would endow the gun with an almost artillery level of flexibility.

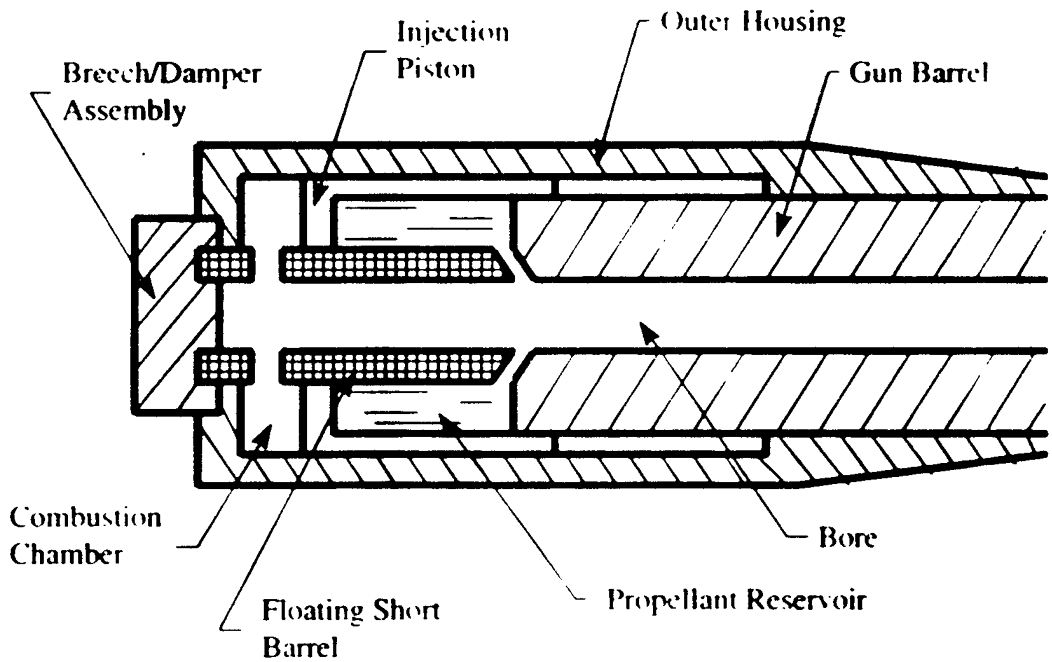

Figure 8. Floating Short Barrel Schematic.

From a propellant efficiency of use standpoint, it would also be highly desirable to vary the volume of propellant in the reservoir. No design concepts for incorporating such a feature into the RAP have yet been investigated. If successful, there would cease to be any distinctions

between a tank gun and an artillery gun. Having a dual gun of this nature would be problematic, however, from a system standpoint. If it were to be used as an artillery gun, then it should fire rounds optimized for this role, at least a HEAT round fuzed for this possibility. It is not clear that the armor commander would look favorably on devoting scarce interior volume to storing artillery rounds at the expense of antiarmor rounds.

The first problem is to ensure, when implementing a solution to this requirement, that complexity be kept within bounds. It is always possible, at least on paper, to add additional features and components that give any particular system added capabilities, but unless they are well integrated, the resulting design simply lacks the needed robustness. The second problem is that the injection area is now in the form of an annulus rather than a series of small individual holes as it is currently. This may create a problem with high-frequency, high-pressure oscillations. The 30-mm RAP is virtually free of these at the moment,* and so was the initial showerhead configuration, in both 25-mm and 105-mm calibers. The concept VI approach, which does use an annular injection area, had significant oscillations even in 25-mm tests. There is thus a real possibility that this phenomena could be reintroduced, particularly in the larger calibers.

If the main gun is limited to firing current design rounds, then the main danger from the presence of these oscillations would be for the KE round, particularly the fins. The KE round represents a highly sophisticated but highly stressed design operating uncomfortably near its design limits. The fins particularly are not very sturdy, and the presence of rapidly fluctuating, large circumferential pressure gradients could rip them off the projectile body. This issue is important. If significant pressure oscillations are observed in 30-mm firings, it should be investigated in this caliber before scaling up to a large-caliber design.

Another important design consideration is bore injection vs. chamber injection. Pressurizing the bore accelerates the projectile, but for the injection piston to perform its function as a pump,

* A 30-mm RAP, scaled and optimized for the tank gun role, is currently being tested at GD Armament Systems. The measured pressures are free of high-frequency oscillations. Propellant injection into the combustion chamber occurs through an annulus and into the bore through a series of individual holes [6].

the chamber region in front of it must also be pressurized. The RAP has been test fired in the mode described, and also using only bore injection, in the so-called "dual-angle" configuration. Here, half the injection holes in the short barrel are angled toward the breech, to provide more efficient flow in this direction to pressurize the combustion chamber and drive the injection piston, and the other half are angled toward the muzzle. This configuration appeared to be successful at about the 1-km/s launch velocity regime. The high-velocity tests, on the other hand, always incorporated explicit flow of propellant into the chamber as well as the bore, on the theory that high performance required fast rise times and therefore a quick startup of the pumping action of the piston. Theoretically, this consideration would be even more important for a larger caliber gun, as the gas velocity would remain unchanged, but the distances to be covered would be greater.

The problem with injecting into the chamber is how to seal this flow area during propellant fill. Considerable development work was done at GEAS working with a 30-mm RAP test fixture with annular seals that sealed at low-pressure gradients but floated free (aerodynamic lift) at high-pressure gradients. However, this work was done with OTTO Fuel II, which has not shown the same sensitivity to initiation by other means as the HAN-based propellants. Furthermore, scaling such seal designs to large caliber is not trivial. This is another area that needs serious design consideration and experimental test.

Ignition, on the other hand, should not be the problem that it is for the artillery application. The reason is that mechanical handling of the rounds, particularly the KE round, will require a stub case that encapsulates the fins. This stub case can be used to perform several important functions. First, it can incorporate an SP ignition charge. Second, it can act as a one-time disposable seal, permitting the use of a simple, drop block breech design. Third, it could conceivably be used to incorporate a break link, permitting a shot start, which significantly exceeds what is available with today's systems and could be advantageous for achieving high velocity. The key question here is how much the strength of the base plate would have to be increased to ensure that it does not fail before the break link.

The key to successful direct-fire engagements is fast response. Projectile and propellant insertion should not impact the time that the gunner needs to acquire the target, lay the gun on it, implement any lead corrections, and fire. Particularly in a meeting engagement, this timeline can be quite short. A good figure of merit for propellant fill time is on the order of 0.5 s. A study performed by Aerojet indicated that a power of 100 hp could sustain a firing rate of 73 rounds/min, more than adequate for the armor mission.* Among the other conclusions of this study were that, if the propellant reservoir was pressurized to a relatively low value during propellant fill, delays between fill and firing of as much as 0.5 s would not produce excessive leakage around the injection piston seals.

In summary, there are cogent arguments for considering an LP tank gun. First, an LP tank gun integrates better into the platform than does an SP tank gun and is capable of providing higher firing rates. Second, the incorporation of LPTC has the potential for improving velocity by as much as 16% for the same launch mass (assuming that additional velocity is truly desirable from an armor penetration standpoint). Third, there is the potential to increase round storage by as much as 50%. Lastly, storing the two propellant components separately can dramatically reduce the possibility of K-kill without requiring the same mass of heavy armor as would an SPG.

8.4 AAN Considerations. If the FCS total vehicle weight is truly limited to the range of 15 tons, the current armament package would represent about 25% of the vehicle weight. The platform would be little more than a carrier for the weapon, with little or no ability to accommodate crew, ammunition, sensors, communications, fuel, and certainly not armor of any significance. Lack of platform stability due to the effect of recoil would be an almost minor consideration. Incorporating into such a light vehicle main armament with sufficient overmatch to efficiently kill all presented threats is so challenging that it requires a re-examination of the basis for today's main armament.

* This study was performed by Aerojet in 1993 under contract to Martin Marietta Defense Systems. This study was part of an internally funded effort to investigate the feasibility of an LPTC tank gun.

8.4.1 Target Kill Mechanisms. To begin with, it is not the gun that kills targets, it is the projectile that the gun launches. The projectile represents the kill mechanism used to defeat the target, and the gun is designed around the launch requirements of the projectile package. Thus gun design is driven by target type and the kill mechanism required to defeat that target type. The first important point is that if neither of these changes, then neither will the gun solution.

Detailed speculation concerning future targets and novel kill mechanism is beyond the scope of both this effort and the author's competence. It is difficult to imagine, however, that within the fielding time frame of FCS (circa 2020) that the defeat of heavy armor, improved even over today's armors, will not be a requirement. Many of the MBTs in existence today will still be in the inventory of both friendly and unfriendly powers. Historically, three mechanisms have been used to defeat such armor: HESH (high-explosive squash head), HEAT (the shaped charge jet), and KE (armor-piercing [AP], fin-stabilized, discarding sabot in its most modern version). Using HESH, the gun sends out a relatively low-velocity round, which, on impact, spreads the explosive charge over a portion of the outer surface. Subsequent detonation then spalls metal chunks off the interior surface, which then disables the vehicle. This kill mechanism has fallen into disfavor. In HEAT, detonation of the warhead generates a jet of molten metal, which then melts its way through the armor. It is the secondary choice against armor, having only limited behind-armor effects. It is, however, very effective against all other targets and is the round of choice against everything but the heaviest armors. In KE, a long, very dense rod melts its way through the armor. Since the required energy comes from the KE of the projectile, the required impact velocity is very high, on the order of 1.5 km/s or better. It is very lethal, because of the behind-armor effects of the remnants of the rod that penetrate, and it is the requirements of launching this projectile package that have driven the design of all modern tank guns.

Novel projectile launch mechanisms, such as EM or ETC (or even Integrated Rocket/Ramjet) do not unfortunately significantly alter this equation. These are all different means of launching the same payload. Their size, weight, use of expendables and power requirement characteristics vary considerably, and therefore so does their impact on the platform that carries them. However, they do not materially change the kill mechanism. They still fire either a KE

penetrator or a HEAT warhead, and their size, weight, and other characteristics are still driven by the launch requirements of these two kill mechanisms.

In considering the list of possible future targets, this author believes that the attack helicopter, or its descendant, must be added to this list. It is already one of the chief threats to the current MBT, and its capabilities will only improve with time. It therefore appears imperative to give the FCS a capability to counter it. However, the helicopter is a relatively vulnerable platform. Existing guns and projectiles already have more than enough overmatch. The problem is rather one of target acquisition, fire control, and projectile fuzing and is therefore not germane to the following discussion.

Another imponderable in this equation is the architecture of the FCS. A one-platform solution to the stated requirements may not be technically feasible. It may therefore consist of a two-vehicle family, one of which could be the descendant of today's attack helicopter. In this scenario, it is conceivable that each component of the total system may be optimized for a particular class of targets, although both would retain some capability against all targets.

It will take a great deal of analysis, balancing desired operational capability against projected technological possibilities, to achieve a rational solution to this puzzle. The following discussion is not intended to present a definitive solution. It is rather intended to discuss possibilities sufficiently to illustrate the role that LP-based main armament might or might not be capable of fulfilling in such a scenario.

8.4.2 Missile vs. Gun Launch. It is this author's contention that, within the context of the FCS requirements as currently stated, neither a pure gun nor a pure missile solution is viable. The former, even if it is limited to firing HEAT only, will be too heavy, the stowed load probably too small, and the recoil forces uncomfortably large. Recoil would not be a problem for a missile. However, missiles are relatively large, and therefore the stowed load would be small. It would be smaller still if the missile is armed with a KE warhead, which requires impact velocities on the order of 1.5 km/s in order to be effective. This is because of the significant

increase in propulsive plants required to boost the missile rapidly to such high velocities. If the impact velocity is kept low and the rod is merely lengthened proportionately (which is possible, at least in principle, given that the launch environment as defined by acceleration level is rather benign), the increased missile length would still result in what would probably be an unacceptable stowed load. Given the size of the FCS, this would probably be on the order of a dozen or less. Stowed load is a serious problem for FCS. Even if gun launch were the sole propulsion mechanism for all ordnance, it appears highly unlikely that more than 20 rounds could be stored on board, assuming 120 mm caliber.

Note that significant reductions in missile motor size, and therefore in the total missile, are possible using significantly higher energy density propellants. However, this would only exacerbate the system vulnerability problem described later.

There is also the nontrivial system design problem of ensuring that all the on-board missiles can be launched from under armor. Currently, vehicle-launched missiles are fired from racks of four launch tubes and then manually reloaded. MLRS, which was purposely designed for its role, employs more launch tubes, but it is also loaded by hand, and the reload is not done under armor. External, manual reload for the direct-fire role is simply not feasible operationally. It is possible to design a system where the missiles are automatically reloaded. The U.S. Navy has been doing this for decades. However, such systems are extremely large and complex, do not form a factor compatible with a ground combat vehicle, and are simply not compatible with the idea of small size, weight, and power requirements, at least not within the FCS context.

Ten to 12 missiles may not represent an appreciable stowed kill, but it does present a serious own vehicle K-kill vulnerability problem. These missiles are relatively large, typically running between 5 and 8 ft in length, depending on the velocity to be reached, and on the order of 6–9 in in diameter. The bulk of the presented area is filled with SP, whose intrinsic vulnerability is considerably less than that desired. Converting to a less vulnerable propellant will not be easy. The energetic considerations are even stronger than for high-velocity guns, as the entire missile structure must fly. Furthermore, if the warhead is HEAT, it is no longer protected by heavy

steel, as it is no longer necessary to withstand the high-g launch environment of the gun. Its vulnerability will be significantly higher than for today's HEAT rounds.

Careful examination of this line of reasoning (it must be emphasized that this is not the only line of reasoning possible) indicates that a combination of gun and missile, still based on the HEAT and KE kill mechanisms, may be worth considering, coupled with the use of LPs (though not necessarily HAN-based) for propulsion for both stages. Guns are exceptionally efficient accelerators until the launch velocity reaches about Mach one. First order calculations for a typical missile design (120 lb total weight, half of it propellant) indicate that the rocket expends one-third of its propellant achieving only one-quarter of its final velocity. A gun would be more efficient at accelerating the remaining missile and propellant up to this velocity, with the propellant on board the missile providing the rest of the velocity increase. (This is essentially the theory of the TC, except that the second stage of acceleration would occur outside of the gun barrel.) The impact on the missile would actually be greater, because the missile structure required to house and support that portion of the propellant would also be eliminated. Such a gun design would have to be very carefully thought through to ensure that its size and weight are minimized, that the launch conditions are soft enough so that the missile structure need not become unduly heavy, and that the recoil is tolerable. First order analysis, such as that represented by CONPRESS [19], should be sufficient to set the basic parameters.

An interesting variation on this theme is the case where external rocket propulsion is limited to the KE warhead, all other rounds being launched on gun power alone. This implies a lower launch velocity for these other rounds than exists today and could compromise hit probability. For FCS, this is not tolerable. Given the small stowed load, it becomes imperative that stowed load be equivalent to stowed kill. This means two things. First, the kill mechanism must have the needed lethality. Second, the hit probability must be one, which requires that all rounds be guided. This latter is not incompatible with the idea of some level of on-board propulsive capability for the projectile. Achieving such a capability will be technically quite difficult and is merely only one indication of the technical difficulties associated with implementing the FCS concept. One of the rewards of successful implementation would be a serious capability against

rotary-winged aircraft. Of course, the target acquisition part of this equation would also have to be solved. Such a capability would also be required if tank extended range munition (TERM) is to be implemented in FCS.

The TERM is an interesting concept when applied to what has traditionally been a direct-fire weapons system, such as FCS. First, it implies an organic capability to see "over the horizon," which does not currently exist. Second, unless a round can be developed, which has satisfactory capability against the full range of targets, it places even greater stress on the very limited ammunition carrying capability of a system like the FCS, as many more varieties of ammunition would have to be carried. The impact on the launcher depends on precisely what the TERM turns out to be. Current tank gun designs, even the short-barreled 152 mm on the M60A2, have more than enough power to launch ordnance beyond visual range. The operational implications, however, will have to be carefully addressed. One of the primary drivers for this is the severely limited stowed load capability of FCS. Resupply (even though this currently requires that the vehicle withdraw from combat) may have to be frequent, certainly so compared to today. This may require a dedicated ammunition resupply vehicle such as exists today for supporting self-propelled artillery.

There is also the interesting possibility of carrying multiple weapons and apportioning the targets of interest among these weapons. One example could be a large gun optimized for the launch of KE alone paired with a minor-caliber gun such as a 40 mm to handle all other targets. Another would be pairing an antitank guided missile (ATGM) with a 40 mm. The two-gun case would probably result in a larger, heavier total armament system, but may have the potential to reduce system vulnerability. A significant limitation of the latter would be response time, particularly in a meeting engagement. Missiles, at least as currently designed, take too long to fly out to the target.

8.4.3 Use of Energetic Liquids. If the previous line of reasoning does represent a potential approach, then what role can energetic liquids play in the propulsive needs of such a scenario? This author believes that their role could be very important and is worth examining in more

detail. The benefits would be the traditional ones, larger stowed load, higher firing rate (which, given the limited stowed load, may no longer be desirable), and improved performance (via TC if implementation of a hypervelocity capability is critical). However, it is their potential benefit in limiting K-kill vulnerability that may be most important.

An earlier argument indicated that a combined gun/missile solution could improve stowed load. Regardless of the vehicle system architecture (manned turret or external gun), all studies have shown that, for gun propulsion, using LPs significantly improves stowed load, up to 50%. However, one must be careful here within the FCS context, with its drastic weight limitation, because the radical reduction in armor will highlight the weight penalties associated with an RLPG compared to an SPG. The flexible form factor of LPs makes it easier to integrate them into complex vehicle configurations. Lastly, there is the question of K-kill (as opposed to F- or M-kill) vulnerability.

The most vulnerable system component in this scenario would be the SP propulsive charges on board the missiles. Reducing the sensitivity of these propulsion charges runs into the same chemistry, physics, and energetics considerations as reducing the sensitivity of SPs for high-performance guns. If anything, the energetics are even more stringent, as the entire missile structure must fly. A straightforward approach to bypassing this contradiction is to introduce energetic liquids into the missile. For this role, the HAN-based propellants simply will not do, not because their sensitivity may not be acceptable in these quantities and packaged according to the dictates of missile design, but simply because their specific impulse is too low. This is not the case for bipropellants such as monomethyl hydrazine (MMH) and IRFNA.

Early Army missiles were liquid fueled. The Army abandoned liquid-fueled missiles in favor of solid-fueled missiles for cogent safety reasons supported by a number of very unfortunate incidents. However, assessments of future operational requirements are already driving the Army to rethink this decision. Specifically, interest is developing in missiles that can be launched at high speed, hover over the target area, and then home in at high speed once targets have been identified. This requires a variable thrust capability that is very difficult to implement

using SPs but is natural for LPs. In this vein, the U.S. Army Aviation and Missile Command (AMCOM) has been re-examining the question of gelling both MMH and IRFNA to make their tactical use in the field acceptable. The combination of these two is quite energetic, and, when separate, their sensitivity is very low.

If such a propellant combination were to be used for the missile part, it would be highly desirable to also use it for the gun part. It would have both energy density and sensitivity superior to that of any HAN-based monopropellant. This would, of course, require the design of an RLPG based on the use of a bipropellant combination. Some effort has already been devoted to exploring this issue. The French appear to have done a number of design studies for an air-to-air minor-caliber weapon based on a bipropellant regenerative design, and in the early eighties, Diehl explored a 30-mm bipropellant test fixture in hardware. This test fixture was built as a scaled version of a 120-mm tank gun, and performance was never acceptable. Analysis indicated that this poor performance was due to poor fuel/oxidizer mixing. Unfortunately, the German program was terminated before potential fixes to this problem could be evaluated.

Another notable feature of the Diehl design was that a hyperbolic mixture was used. Although this did eliminate the need for an ignition subsystem, special care had to be taken with the design to ensure that the two components never came into contact until they were injected into the gun chamber.

These are not trivial design and development challenges. Their consideration is meant to illustrate the difficulty of integrating the Army's desired capability into a 15-ton weapon system. The basic message is that any technology that offers the possibility of maintaining lethality while at the same time reducing vulnerability and maximizing stowed load, should be given careful consideration for the FCS mission. LPGs, even modified as radically as the previous arguments suggest, certainly offer this potential.

Note that one of the primary drivers of the previous logical train of thought is the perceived need to efficiently defeat heavy armor. There are proponents who will say that this will be passe,

that with concepts, such as TERM, the FCS will be able to defeat heavy armor at long range, without exposing itself to counterfire. The lesson that the Air Force has learned over the last 3 decades is stark. Most of the fighter planes that were designed during these decades did not incorporate guns on the theory that all combat would occur "beyond visual range," relying on such long-range missiles as Phoenix. In every case, the reality of combat forced the retrofit of a gun. There is no reason to believe that the Army's experience would be any different.

8.5 Conceptual Weight Comparisons. We end this section with a comparison of SPG and LPG system weight. Although both interesting and important, it must be emphasized again that the most important factor is not the gun system weight (or size) in its own right but rather its impact on the weight (and size) of the platform on which it is mounted.

The first example is a concept study [18] for a 140-mm tank gun based on a RAP RLPG configuration. Three guns were concepted, an RLPG, an SPG, and a TC version of the RLPG, all launching an 11-kg package at 1800 m/s. Table 2 lists the weights of the 140-mm LP RAP and RAP-TC gun system.

Table 2. Summary of 140-mm LP RAP and RAP-TC Gun System Weights

	RAP (lb)	RAP-TC (lb)
Chamber	6394	4120
Barrel	2310	3885
Totals	8705	8000
Projectile Weight (50 rounds, 2/3 KE, 1/3 HEAT)	1595	—
Propellant Weight	2060	—
Fill System Weight	905	—

The difference between the RAP and RAP-TC weights is due to two factors. First, the RAP-TC barrel was made heavier to accommodate higher expected down-bore peak pressures, but the increased ballistic efficiency permitted a 25% reduction in the required propellant charge, reducing the chamber size and weight.

The weight of the equivalent performing concepted 140-mm SPG was 6190 lb. The weight of the ammunition, distributed between KE and HEAT in the same ratio, was about 4400 lb. The SP barrel was essentially equivalent to the RAP barrel, the barrel pressure profiles being very similar.*

As mentioned earlier in this report, a full system analysis based explicitly on the user's requirements concluded that the weight differential between the RLPG and SPG would be more than compensated for by the superior ease of integration of the LP gun system vs. the SP gun system [18]. Some general characteristics are worth noting. First, the chamber dominates the weight of gun. Second, for both the LP and SP guns, the ammunition weight is significantly less than the gun (chamber plus barrel) weight.

Several additional tank gun design explorations were performed by GEOS under in-house funding. The first is taken from a study performed by Aerojet under contract to GEOS, with the primary purpose of the effort being delineation of how LPTC could be realistically incorporated into a 120-mm tank gun. Particular care was taken to design a propellant fill system that could load the gun in 0.1 s, thus ensuring both transparency of the projectile/propellant process to the user's timeline for engaging the target and concern about excessive propellant leakage into the combustion chamber prior to firing. Ballistic analysis indicated that a 120-mm KE round could be launched at a 16% increase in muzzle velocity (1946 m/s). However, the gun weight grew significantly, to almost 6600 lb, as opposed to the current value of the SP 120 mm of about 4400 lb. Note that the RLPG is consistently 30–50% heavier than its SP counterpart for equivalent performance.

The second design study was performed in 1986 for the purpose of exploring solutions that would maintain the 120-mm gun weight but would significantly improve its performance within this weight envelope. The basic design concept was an RAP-TC, but with a 135-mm rather than a 120-mm bore, and an extra long projectile travel of 6.1 m. Gun weight was kept low by limiting peak chamber pressure to 60 ksi. Total gun weight was about 4540 lb, with the chamber

* All barrel designs in this study were performed by Rheinmetall GMBH of Germany.

weighing 2000 lb and the barrel 2540 lb. Ballistic analysis indicated that such a design could achieve a velocity of about 2 km/s. However, round storage would be decreased by about 25–30% due to the increased diameter of the rounds, and the long gun barrel could present an overhang problem. This design concept is illustrated in Figure 9.

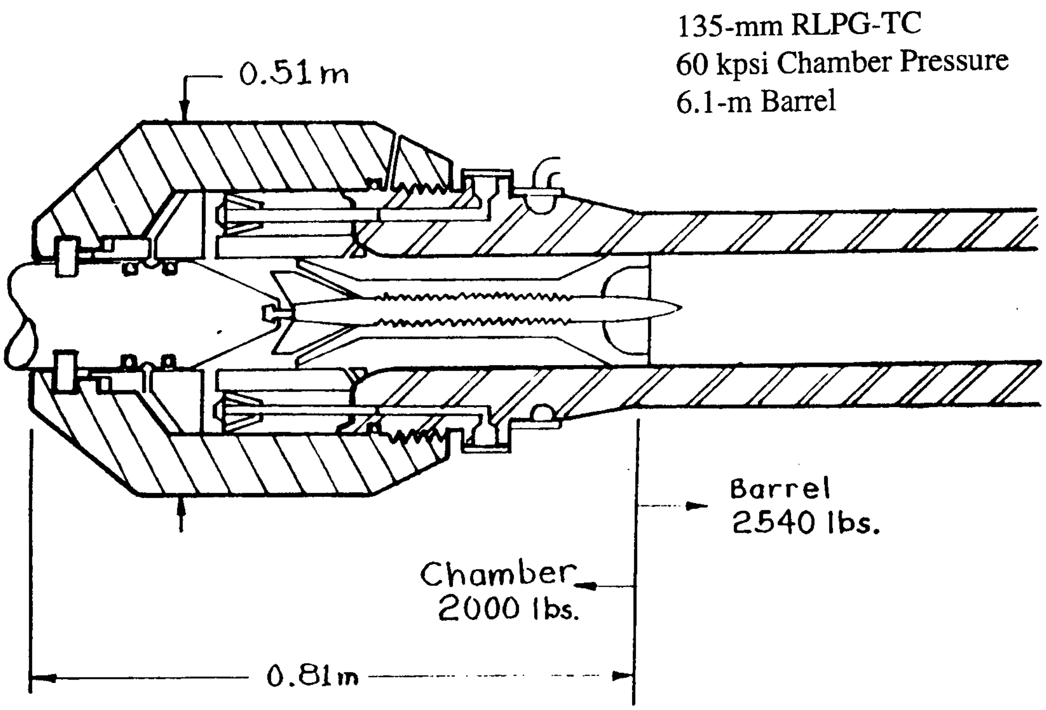

Figure 9. Schematic of Lightweight 135-mm RAP-TC.

The hybrid TC approach (LPTC, SP breech charge) continues to appear particularly attractive from a gun weight standpoint. This is illustrated in Figure 10, which compares gun weight against performance for conventional and hybrid TC designs, keeping the launch mass and gun caliber constant.* The weight savings in the hypervelocity region are dramatic. This chart is of particular interest because, even if predictions are off by 50%, the weight differential between the SP and SP/LPTC designs is still very significant.

* This analysis was performed by GEOS under in-house funding during the early eighties.

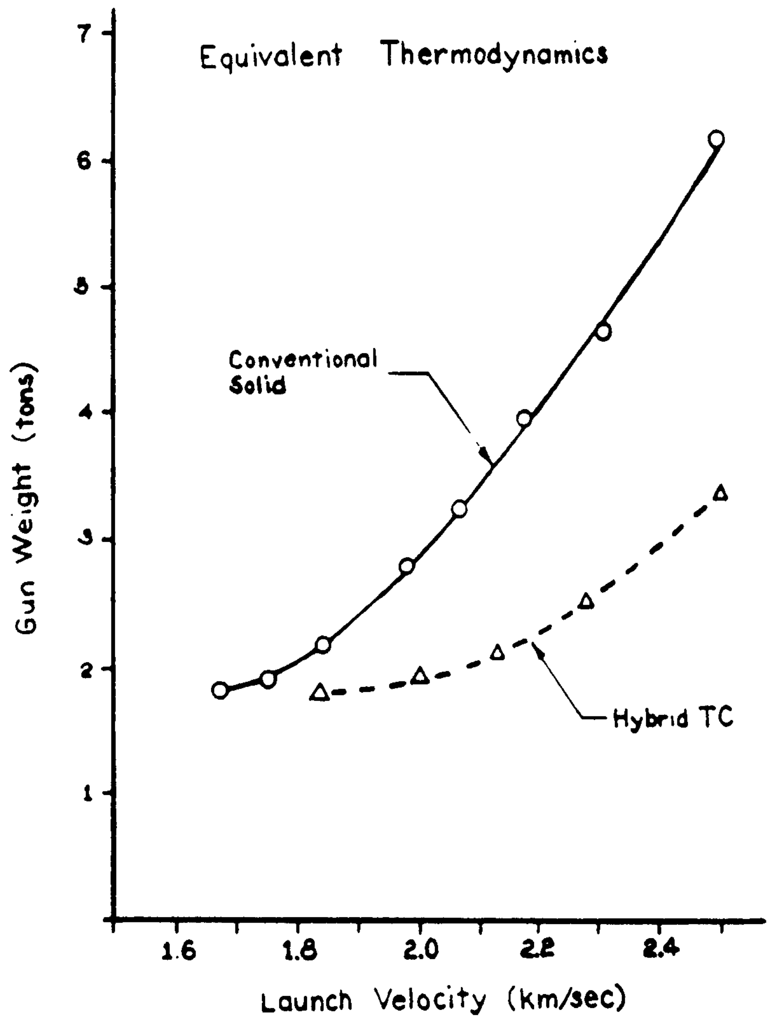

Figure 10. Conventional vs. Hybrid Weight vs. Velocity Comparison.

9. Minor-Caliber Applications

9.1 System Considerations. For the Army, minor-caliber weapons support three missions: ground-to-ground, ground-to-air, and air-to-ground engagements. Calibers range from 20 mm to 40 mm and both high-explosive (HE) and KE projectiles of various types and sophistication are fired. Velocities are typically in the 1-km/s range with firing rates on the order of 500 to 1000 rounds/min. The ground-to-air engagement is an exception. Here the target is typically a highly maneuvering air platform, and the highest possible velocity is desired in order to reduce

the time of flight.* Such weapons typically have much higher firing rates, these being achieved by clustering several gun barrels together in a Gatling configuration.† Most of these weapons employ a burst limiter‡ to ensure optimal use of the on-board stowed load.

Consider first the ground-to-ground application, as exemplified by the primary weapon on the Bradley Infantry Fighting Vehicle (IFV), in both its M2 and M3 versions. From a systems perspective, the first point is that, unlike the case for the Abrams, the gun system represents only a very small fraction (less than 1%) of total system weight. This application is more tolerant of increases in gun weight, provided that they yield a truly superior systems solution. Second, the propelling charges for the gun ammunition do not represent the most vulnerable system component. That role is now played by the propellant in the rocket motors of the on-board tube-launched, optically tracked, wire-guided (TOW) missiles. This again permits greater scope for armament system improvements without significantly impacting overall system size, weight, and vulnerability requirements.

The driving factors for improved performance are no different than for any other direct-fire weapon, though perhaps less dramatic in scope. Foremost is a strong desire for improved performance against the most heavily armed and armored targets. This is complemented by a desire for more stowed load and reduced cost and vulnerability. All are achievable using LPGs.

The requirements for this mission dictate a rapid-fire gun, with typical firing rates on the order of 500 rounds/min. It is highly desirable to minimize the size of the moving breech element, both to reduce the need for large swept volume and the power required to cycle these elements in times consistent with the firing rate, particularly if the breech is externally powered. Since it is a direct-fire weapon, only two or three types of rounds are fired, and they are launched at fixed velocities. Thus the type of fine precision control over variable velocity that is

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* For unanticipated target acceleration, miss distance is proportional to the square of the time of flight.

† In such weapons, there is only one receiver for the rounds. The cluster of barrels is motor-driven at high rotational speed. This permits very high firing rates, on the order of several thousand rounds per minute, without melting any gun barrels.

‡ A typical burst length is 50 rounds.

characteristic of the VIC RLPG configuration is not needed, and the natural choice is a RAP-type RLPG configuration.

The weight differences between an LPG and an SPG are not as dramatic in this application as they are in a tank gun. Table 3 lists the weights of the main elements of the Bushmaster single-barreled 30-mm gun.

Table 3. Weights of Main Elements of Bushmaster 30-mm Gun

Barrel	150 lb
Receiver + Feeder	176 lb
Ammunition (500 rounds, less storage drum and feed chutes)	750 lb

For its RLPG equivalent, the barrel weight would be the same. The length of the solid object being rammed into the receiver would go down by about a factor of two,* thus reducing receiver length and therefore weight by about two. However, given the increased receiver diameter required to house the regenerative pumping parts, the weight would again about double, resulting in no appreciable net change compared to the SP case. Note, however, that the weight of the ammunition dominates the total system weight, even when not accounting for its storage and feed mechanisms. The combined projectile and charge weight for the LP case for 500 rounds would be about 583 lb. Considering only these elements, the LP system would be about 20% lighter than the SP system.

The difference is actually greater. Table 4 lists the characteristics of the GAU-8/A, a seven-barrel, 30-mm Gatling gun.†

These data indicate that the total system weight is driven primarily by the ammunition and ammunition storage and feed elements of the total system. These elements are six times the

* Total cartridge length is 11.4 in, while the projectile length is 5.6 in (information supplied by GEAS).
† Data supplied by GEAS.

Table 4. Weight/Capacity Characteristics of GAU-8/A 30-mm Gun

Total System Weight	3875 lb
Gun Weight	618 lb
Ammunition Capacity	1174 rounds
Round Weight (Armor-Piercing Incendiary [API])	1.5 lb

weight of the gun itself. For this case, the reduction in ammunition weight by converting to LP would be about 330 lb. The weight reduction in the ammunition storage and feed system, due to the reduction by a factor of two in the length of the object being stored, would be about 1034 lb. Thus converting to LP would result in a weight savings for the system as a whole of about 35%.

The reduction in total gun system volume would be equally dramatic. The total gun system volume is dominated by the space claims of the ammunition storage and feed system. This would be reduced by almost a factor of two, thus reducing overall system volume by about 40%.

Figure 11 illustrates the results of a design study for a minor-caliber air-to-air gun in a Gatling configuration. Note that, unlike the case for a large-caliber gun, the chamber size does not dominate the design. The additional mechanization necessary to support ammunition feed and powered operation, together with the barrel cluster, dominates the size and weight budget.

Figure 12 illustrates the size of the bullets that must be mechanically handled and inserted into the gun chamber at high rate. Shown in this figure are conventional, cased telescope,* and LP 40-mm rounds. The LP round is dramatically shorter and smaller in envelope than either the conventional or cased telescope rounds. This permits a shorter receiver and bolt stroke, and requires significantly less power to support the same firing rate (particularly important if, for reasons of reliability, the gun is externally powered). Of course, once the conventional and cased

* In the cased telescope configuration, the projectile is completely buried in the cartridge case, surrounded by the propellant. This has the system advantage of significantly shortening round length.

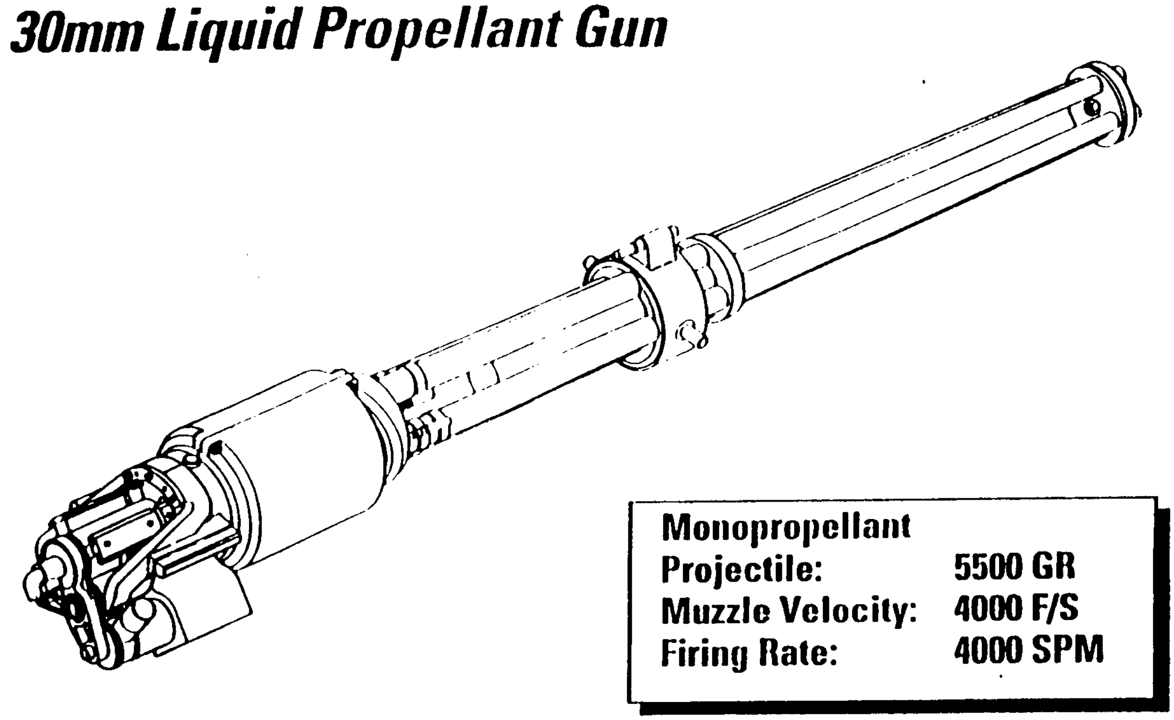
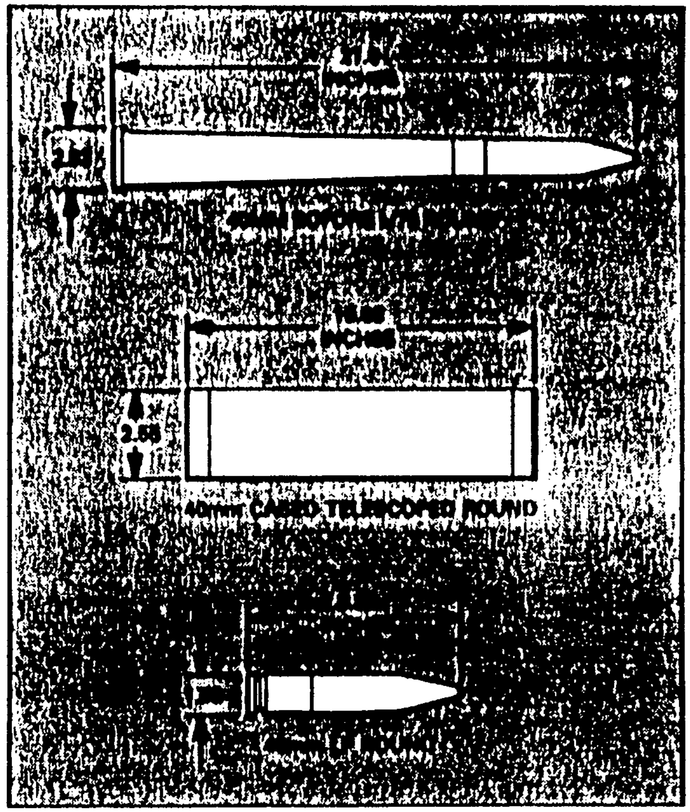


Figure 11. 30-mm RAP RLPG Gatling Configuration Concept Design Study.

telescope rounds are loaded into the breech, there is nothing further left to do. This is not the case for the LP round, where the propellant still has to be inserted into the gun breech. In spite of the need for a separate PSHS, several design studies have indicated that the LP-based system would still be significantly lighter and smaller than its SP-based counterpart for equivalent performance, firing rate, and stowed load.

Figure 13 is an illustrative sketch of the elements that make up an LP armament system for this mission. An actual propellant fill system, of course, would be significantly more complex. The flex chuting that guides the rounds into the breech would be smaller, permitting sharper bends and taking up less space. As illustrated, the propellant tanks could be conformal, further reducing the volume required. The impact on volume required to store equivalent numbers of rounds is dramatic, as illustrated in Figure 14. This analysis indicates that the number of complete (projectile plus propellant charge) LP rounds that can be stored in the same volume is about three times larger than for conventional rounds and about twice as large as cased telescope



The Reduced Size of the LP Round Provides a Dramatic Improvement in Ammunition Storage Density Compared with either Conventional or Cased Telescoped Ammunition

Figure 12. Comparison of 40-mm Conventional, Cased Telescoped, and LP Round Sizes.

In-Vehicle LP Storage and Supply

Schematic of LP Storage and Supply System
Featuring a Conformal LP Storage Tank

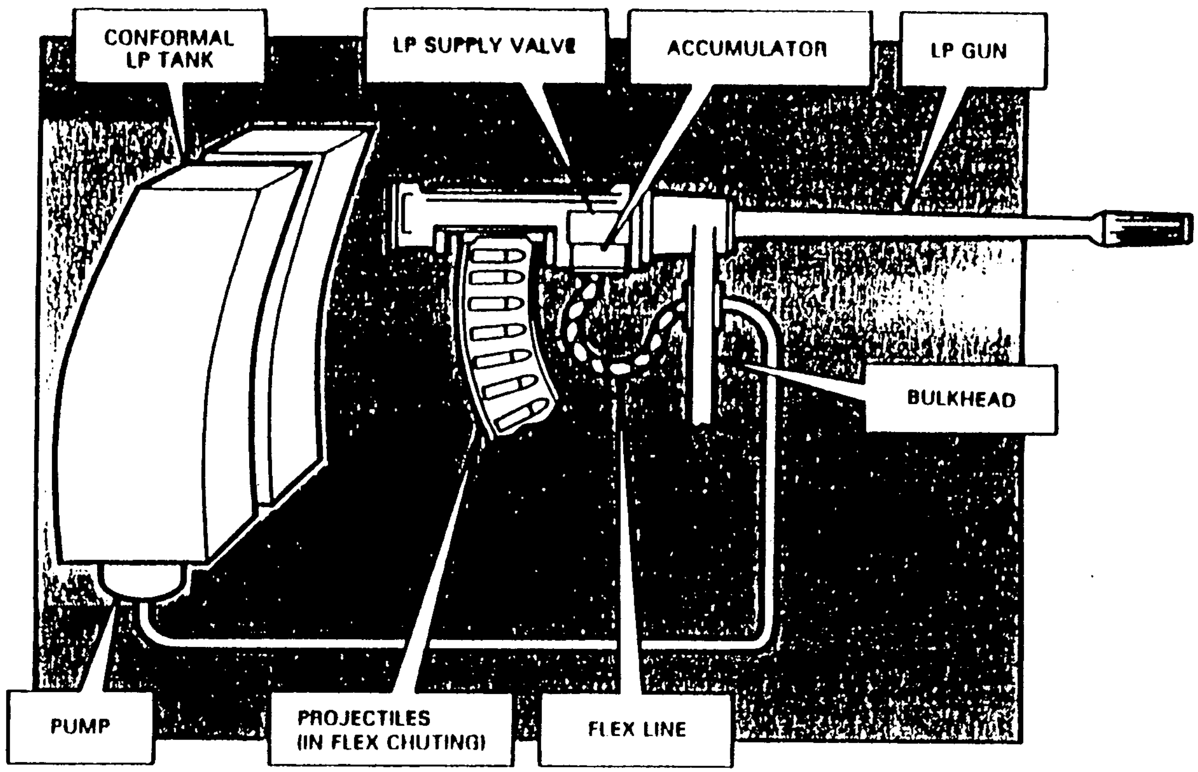


Figure 13. Typical LP Armament System Elements.

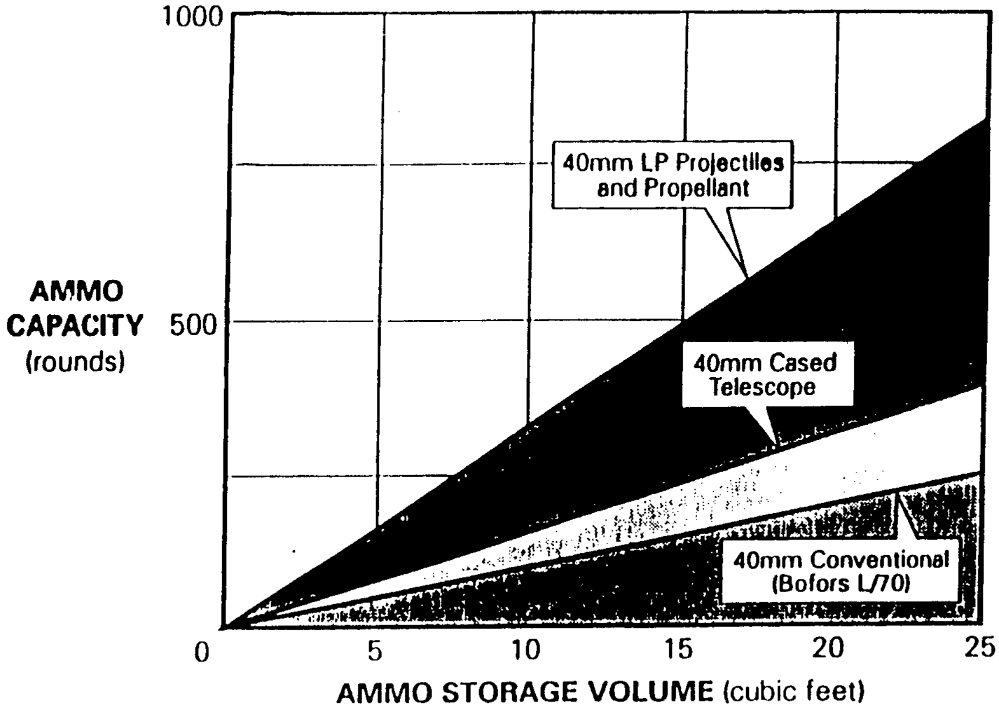


Figure 14. Comparison of 40-mm SP, Cased Telescoped, and LP Ammunition Storage Capacity.

rounds. This again indicates that, for equivalent capability, an LP armament system would also be significantly lighter. Unlike the case for an MBT, the stored propellant charges no longer represent the most vulnerable element in the system. Weapon systems armed with minor-caliber guns, be they ground or air platforms, are also typically armed with several large-caliber HEAT armed missiles. It is the propulsion charges of these missiles that dominate the issue of K-Kill.

Weapons of this type typically fire two types of rounds, HE and KE. The HE round may or may not be proximity fused. The missions are ground-to-ground, air-to-ground, and ground-to-air. The first two place no unusual demands on gun performance for launch of the HE round. The KE round is a different matter. There continues to be a strong desire to have the ability to destroy the hardest possible armored targets using these weapons, a desire that places great emphasis on launching the KE round at the highest possible velocity. In terms of the LPG vs. SPG tradeoff from a system perspective, the considerations are the same as for the high-velocity

tank gun discussed in section 8. Similarly, so are the conclusions. For equivalent gun performance, as measured by both launch velocity and stowed load, the LPG will occupy less space and make a smaller contribution to system K-kill vulnerability. Furthermore, because of the size and weight of the machinery needed to support the high rate-of-fire requirement, the difference between the combustion chamber weight of the SPG and LPG is a much smaller fraction of the total armament system weight and the two should therefore be roughly comparable. Finally, the discussions with respect to LPTC also apply directly. This propulsion technique offers the possibility of achieving hypervelocity performance with the smallest required growth in armament system size and weight, and the least reduction in stowed kills.

The driving considerations for the ground-to-air role are different. Here the targets are relatively soft-skinned and vulnerable but are far more swift and maneuverable than any ground target. The emphasis, therefore, is on a short time of flight, no matter the nature of the projectile. The reduction in miss distance goes as the square of the reduction in the time of flight. (This analogy, of course, cannot be pushed too far. The photon has zero time of flight, but it has virtually no damage-producing capability when it arrives at the target.) The bulk of the system-level considerations are the same as for the two applications discussed earlier, such as system size, weight, and stowed kills. However, the emphasis on reduced time of flight is so strong that all propulsion techniques that promise significant reductions in this parameter are worthy of consideration. This most emphatically includes LPTC.

9.2 Remaining Development Needs. The development of RLPG minor-caliber weapons reached its highest level at GEAS during the late seventies and early eighties culminating with the test firing of a 30-mm fully functional, externally powered prototype designed to fire at 1000 rounds/min using OTTO Fuel II. This gun was actually test fired at rates in excess of 400 rounds/min in five-round bursts. In several test series, the third round was deliberately disabled to demonstrate the self-clearing capability of this design. The mechanism worked as designed. The projectile incorporated a small stub case to provide obturation, contained a small SP charge to provide ignition, and it was also used for round control. A picture of this test fixture is shown in Figure 15.

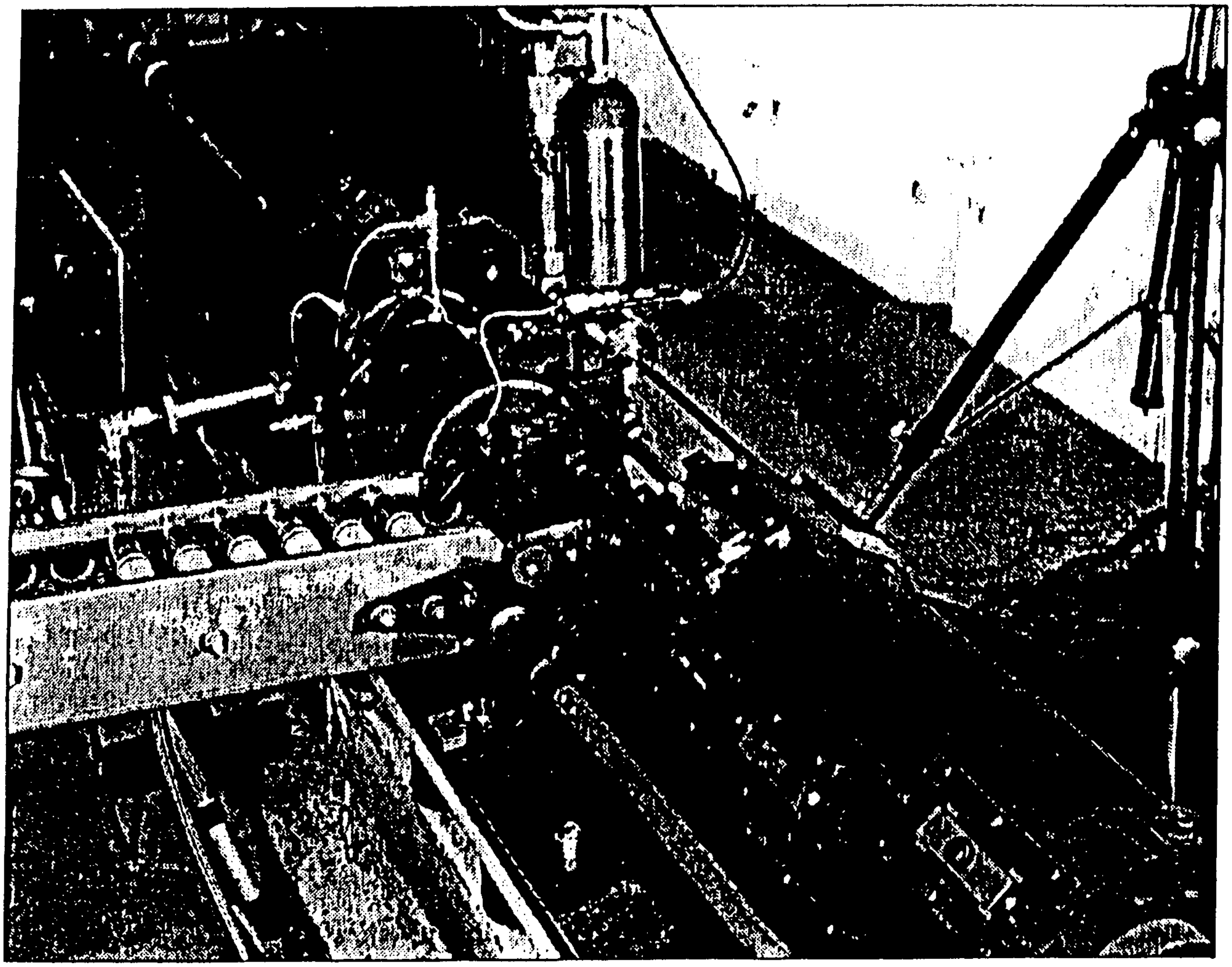


Figure 15. Picture of 30-mm RAP RLPG Burst Fire Test Fixture.

This RLPG prototype minor-caliber design worked very well using OTTO Fuel II as the propellant. However, OTTO Fuel II is not an acceptable gun propellant. Its energy density is too low, and its combustion results in excessive soot formation. Furthermore, considerable circumstantial evidence indicates that it may be significantly more resistant to the ignition sources that have on occasion produced undesired ignitions in test fixtures using HAN-based propellants. This same test fixture was also successfully fired in a single shot mode using HAN-based propellants. Burst firing using HAN-based propellants at rates approaching 400 rounds/min was never attempted, and it still remains to be demonstrated that this can be done successfully.

The dual angle injector configuration (reference description in section 8.2.1) probably removes one of the important barriers to successful implementation (assuming, of course, that burst firings are successful using HAN-based propellants) of an RAP RLPG. For a given caliber, the weight differential between the different projectiles fired at that caliber rarely exceeds 20% and is usually less than 10%.* Thus, unlike the case for the tank gun, it may not be necessary to further complicate the gun design by adding such additional sophistication as a floating short barrel (see Figure 7) to control propellant flow rate for the different types of rounds.

10. Defense Against Tactical Ballistic Missiles

TBMs may be armed with either conventional warheads or with nuclear, chemical, or biological warheads. They are employed either against high-value point targets (conventional or nuclear warheads) or as an area weapon (nuclear, biological, or chemical), against both civilian and military targets. Thus a key requirement is to intercept them far enough away from their intended target that even if the warhead is detonated, the collateral damage is minor. The keepout range thus tends to be on the order of 5–10 km. Both missiles and gun systems have been investigated for this defensive role, including tiered systems employing both missiles and guns. Various system studies have indicated that a gun-based defensive system would require high firing rates, on the order of several per second, and some form of terminal and/or command guidance. The projectile must pass very close to the target missile to be effective, thus requiring a very precise and sophisticated fire control system. The projectile must get out to intercept range quickly, to allow firing of additional projectiles as needed, and typically maneuvers by using aerodynamic braking.

These considerations place the following requirements on the gun system. The projectile must be medium- to large-caliber to encompass warhead, guidance, and maneuver elements. To have a short flight time to the ranges of interest, and to have sufficient residual KE to perform

* Based on projectile data supplied by GEAS. It spans the caliber range of 0.50 cal. to 40 mm and includes AP, armor-piercing discarding sabot (APDS), HE, high-explosive incendiary (HEI), high-explosive incendiary tracer (HEIT) and other types of rounds.

the necessary terminal maneuvering, it must be launched at hypervelocity, on the order of 3 km/s. It must have a high firing rate for short bursts, on the order of several per second for perhaps five rounds, significantly more than typical guns of this caliber. It is a special-purpose weapon and would not see a great deal of use, so that considerations such as barrel erosion would not be a great concern. It would have to be complemented by a target acquisition and fire control system of considerable sophistication. Although it is highly desirable that it have high strategic mobility, to allow quick introduction into the theater of operations, it need not have the same level of tactical mobility as, say, an MBT or an IFV.

Conventional propulsion cycles, based either on SPG or LPG, are simply not appropriate for this application. The required launch velocity is beyond their reach. The LPTC, however, is an ideal candidate for such an application. To date, there has been little work done on this approach. GEOS, in the early eighties, did perform some design studies for such a gun system, based on the LPTC. The results indicated that a 175-mm gun firing a subcaliber projectile (less than 100 mm) could achieve the desired performance. This cursory design study also indicated that the design of the ammunition feed system to support the necessary firing rates and burst lengths was also feasible. This study assumed, of course, that the LPTC could be reduced to practice. Given this assumption, however, the next highest risk turned out to be design of a target acquisition and fire control system of sufficient accuracy and range.

However, for this application, the LPTC solution cannot be regarded as strongly preferable to other novel gun propulsion approaches such as EM or ETC. The reason for this is that tactical mobility is simply not that critical. The two propulsion techniques mentioned previously, while by no means as yet reduced to practice, are both capable of achieving the necessary launch velocities. They will all have essentially the same difficulty at the system level with target acquisition and fire control. The EM-based system would be the heaviest, the LP-based the lightest, and the ETC-based system would be somewhere in between, probably closer to the weight of the LP-based than the EM-based. The key point is, however, that because of the lack of emphasis on tactical mobility, system size and weight are not key discriminators, and other factors, such as development cost and risk, would drive the selection.

11. Summary and Conclusions

The unique aspects of LPGs stem directly from the fact that they employ liquid rather than solid propellants. The governing principle is that LPs are far simpler structures than SPs, but, unlike SPs, machinery is required to control them and to burn them properly. They will not stay in one location of their own accord, and this requires careful attention to total system design to ensure the necessary level of degraded mode operation and personnel safety.* In generic terms, this results in the following benefits and burdens listed in Table 5.

From a technological development perspective, LPG technology is not yet ready for application to any mission area. The artillery and minor-caliber applications are the most developed; the large-caliber, high-velocity applications are the least developed. LP-TC offers excellent potential for operation in the hypervelocity† regime, but only laboratory feasibility has yet been demonstrated.

It is traditional in discussing the worth of novel gun propulsion technologies to emphasize their intrinsic potential for launching at high velocity. In this respect, LPGs and SPGs are essentially equivalent. There are, to be sure, limited instances where the ballistics of an RLPG are superior to that of an SPG. One specific case is artillery at high zones. Because it is possible to operate the combustion chamber at close to a constant pressure if the propellant charge is sufficiently large, equivalent velocities can be achieved at significantly lower peak chamber pressures. This can indeed be advantageous in launching acceleration sensitive payloads to longer ranges. However, it must be remembered that this advantage comes at a cost in gun system size and weight. The only truly proper way in which to evaluate military worth is within the total context of the user's mission needs and requirements.

* It is still necessary to transfer propellant to the using platform and to move it around within that platform even if system power is incapacitated. Liquids can spill and can atomize, and there are health consequences to both of these.

† Hypervelocity means velocities in excess of 2 km/s.

Table 5. Benefits and Burdens Comparison Between LP and SP

	Benefit	Burden
Acquisition Cost		WORSE ("startup" costs,[a] more complex)
Life-Cycle Cost	BETTER (the key expendable, far cheaper to produce)	
Logistics	BETTER (economies associated with bulk handling of LP)[b]	
Stowed Load	BETTER (30–50% for LC, 50–100% for MC)	
RAM-D		WORSE (much more complex, lower reliability, higher maintenance)
Firing Rate	BETTER (up to 50% higher potential for LC, unchanged for MC)	
Blast/Flash	BETTER	
Vulnerability	BETTER	
Gun Weight/Size		WORSE (30–50% larger/ heavier for LC, equivalent for MC)
Gun System Weight/Size	MC-BETTER (50–100% improvement)	LC-WORSE (typically 25% bigger/heavier)[c]
Platform Integrability	BETTER	

[a] The manufacturing base required to produce such weapons does not yet exist and would have to be installed.

[b] Studies conducted by several organizations (Jet Propulsion Laboratory [JPL], BDM) have resulted in storage, handling, and transport efficiencies at all nodes in the logistical support train of between 10 and 30%.

[c] This is strongly dependent on breech design and therefore on choice of RLPG configuration. It is also crucially dependent on required launch velocity. For hypervelocities, LPTC offers significant weight and size reductions.

If hypervelocity launch is important for a given mission, then LPTC provides a clear and distinct advantage, provided that tactical mobility is important.* If tactical mobility is not of paramount importance, such as for defense against TBMs, then other propulsion techniques must also be considered and the selection must be based on other factors, such as perhaps remaining technical development, risk, and cost. The minimum weight and volume package for achieving hypervelocity performance is the hybrid TC, with an SP breech charge and an LPTC.

* Here tactical mobility is defined as being integratable into a ground combat vehicle such as an MBT or an IFV. The principal defining parameters of integratability are weapon system size, weight, stowed load, and vulnerability.

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List of Acronyms

AAN	Army After Next
AP	Armor Piercing
APDS	Armor-Piercing Discarding Sabot
API	Armor-Piercing Incendiary
ARL	U.S. Army Research Laboratory
ATGM	Antitank guided missile
CONUS	Continental United States
DTLOMS	Doctrine, Training, Leadership, Organization, Materiel, Soldier
EM	Electromagnetic
ETC	Electrothermal Chemical
FACS	Future Armored Combat System
FCS	Future Combat System
FTC	Fractional Traveling Charge
GEAS	General Electric Armament Systems
GEOS	General Electric Ordnance Systems
GDLS	General Dynamics Land Systems
GPM	Gallons per Minute
HAN	Hydroxyl Ammonium Nitrate
HE	High Explosive
HEAT	High-Explosive Antitank
HEI	High-Explosive Incendiary
HEIT	High-Explosive Incendiary Tracer
HESH	High-Explosive Squash Head
IFV	Infantry Fighting Vehicle
IRFNA	Inhibited Red Fuming Nitric Acid
KE	Kinetic Energy
LAP	Load, Assemble, and Pack
LC	Large Caliber
LCC	Life-Cycle Cost
LGP	Liquid Gun Propellant
LP	Liquid Propellant
LPG	Liquid Propellant Gun
LPTC	Liquid Propellant Traveling Charge
MBT	Main Battle Tank
MC	Minor Caliber
MICOM	U.S. Army Missile Command
MMH	Monomethyl Hydrazine
OOTW	Operations Other Than War
PIMP	Permissible Individual Maximum Pressure
PSHS	Propellant Storage and Handling System
RAM-D	Reliability, Availability, Maintainability-Durability

RAP	Reverse Annular Piston
RLPG	Regenerative Liquid Propellant Gun
SOP	Standing Operating Procedure
SP	Solid Propellant
SPG	Solid Propellant Gun
SPH	Self-Propelled Howitzer
TBM	Theater Ballistic Missile
TC	Traveling Charge
TCD	Traveling Charge Dispenser
TEAN	Triethanol Ammonium Nitrate
TERM	Tank Extended Range Munition
TOT	Time on Target
TOW	Tube-Launched, Optically Tracked, Wire-Guided
TRADOC	U.S. Army Training and Doctrine Command
WMRD	Weapons and Materials Research Directorate
WTD	Weapons Technology Division

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The primary purpose of this effort is to provide a preliminary assessment, from a weapon system perspective, of the applicability of LP gun (LPG) technology to the U.S. Army's anticipated future gun weapon systems needs, with particular emphasis on the Future Combat System (FCS), the intended replacement for the M1 main battle tank (MBT). The focus is at the weapon system level, as opposed to the details of implementation. Admittedly, these are often far from trivial, but they determine the difficulty of implementation and not the desirability of doing so. The secondary purpose is to provide, based on the current technology development status and as driven by the specific characteristics of the gun weapon systems discussed, the future development needs should the U.S. Army choose to continue development of this technology.

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